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Edited by

O. M. B. BULMAN, S. R. NOCKOLDS, and W. B. HARLAND

assisted by

PROFESSOR W. G. FEARNSIDES PROFESSOR O. T. JONES
PROFESSOR LEONARD HAWKES SIR WILLIAM PUGH
PROFESSOR C. E. TILLEY

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GEOLOGICAL MAGAZINE

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The Subdivision of the Upper D Beds of the Speeton Clay of Speeton, East Yorkshire

By JOHN W. NEALE

ABSTRACT

The confusion that has arisen over the interpretation of the D2—D3 boundary is analysed and a new definitive section of the Upper D Beds is given.

INTRODUCTION

The Lower Cretaceous Speeton Clay crops out in a series of low cliffs north of the chalk cliffs of Bempton on the south side of Filey Bay. J. F. Blake (1891 p. 138), with good reason, has called the outcrops " a wild tumbled slope, in which at first sight it is hopeless to make out any order ", and the lithological divisions of the Speeton Clay currently employed are those due to Lamplugh (1889) who published his succession after ten years careful and meticulous work on the shore sections. Previously Leckenby (1859) and Judd (1868) had made valuable contributions to our knowledge, the latter studying the cliff sections and basing his sub-divisions on the ammonites. Lamplugh concentrated his attention on the shore exposures and the belemnites. He recognized six major divisions of very unequal thickness based on the presence of characteristic groups of belemnites, and to these divisions he gave the letters A to F from the top downwards, i.e., the reverse of the usual stratigraphical practice. The C and D beds were further subdivided into C1–C11 and D1–D8, the numbers again reading from the top downwards. Lamplugh's notation is now generally acknowledged to be the most useful guide to the section and is universally used.

Considerable confusion arose in the past over the thickness, lithological development and age of the D Beds. In part this was due to the difficulty of correlating Leckenby's section with the later work, but it sprang mainly from the misidentification and erroneous correlation of the ammonites from the D Beds. These were originally supposed to be of marine Portlandian and Purbeckian or Upper Volgian age, and even as late as 1920 certain geologists held the view that at least part of the D Beds were of Jurassic age. This was finally disproved by Spath (1924) and the whole matter is now merely of historical interest and is not discussed further. Attention has recently been focussed on another problem which is outlined below.

THE PROBLEM OF THE D2–D3 BOUNDARY

In the D Beds three Lower Cretaceous stages, namely Berriasian,

Valanginian and Hauterivian, are represented in only 45 feet of strata. In consequence, it is of paramount importance that the horizon of all fossils should be accurately localized. If Lamplugh's divisions are misinterpreted, the incorrectly localized material becomes worse than valueless and can only result in confusion if work based on such material is published. This has already happened in the case of Danford (1906a, b) where the boundary drawn between D2 and D3 differs from that originally defined by Lamplugh. Two interpretations of this boundary have thus arisen, and as this has recently become apparent among workers actively collecting this part of the section it seems advisable to re-define this boundary in order to eliminate any ambiguity. The present paper sets out to do this by providing a definitive section of these upper D Beds together with an expanded notation which will be used in papers at present in preparation, dealing with the faunas of these beds.

For a considerable time the sections at Speeton have been poorly exposed due to the protective influence of the concrete defence structures erected during the last war. With the storms of the last two years, these have rapidly succumbed to marine erosion and during the winter of 1959–60 the Speeton section has changed very considerably. Exposures in the D Beds are excellent and it is now possible to see the whole succession in this group at the same time. The confusion that has arisen in the case of the upper beds seems to be due to three factors. The main cause is insufficient familiarity with Lamplugh's basic work and the criteria of his boundaries. The other two factors somewhat modify the sharpness of this criticism since the true thickness of D2 is over twice that recorded by Lamplugh (or nearly four times that adopted by Danford), and the fact that there are two nodule beds within 4 feet of each other is also likely to lead to error.

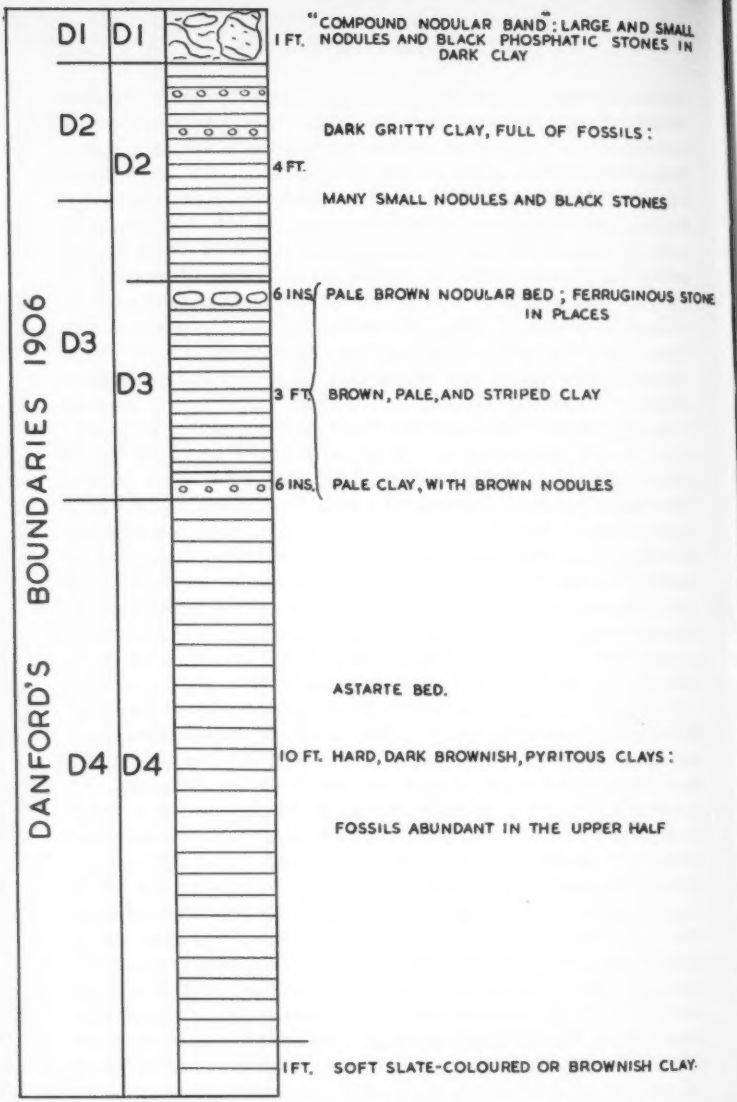
Lamplugh's classification of the D Beds published in 1889 is redrawn here as Text-fig. 1, in which the total thickness of D3 is given as 4 feet, the lowest 6 inches of which consists of pale clay with brown nodules. The top of D3 is defined quite unequivocally (op. cit. p. 587) when he records that " the thin band of clay with nodules which caps these striped beds includes here and there lenticular masses of soft gritty ferruginous stone " and goes on to say that the overlying dark blue and *brownish clay above this band* belongs to D2 and is *about* 4 feet thick (my italics). It will be seen from his section that D2 is defined as 4 feet of " dark gritty clay, full of fossils : many nodules and black stones ".

Whereas Lamplugh gave D2 a thickness of only about 4 feet, the excellent cliff sections seen today show the presence of 10 feet of deposits between the ferruginous nodular bed at the top of Lamplugh's D3 and the base of the Compound Nodular Band (D1). Furthermore

there is a marked colour change some 2 feet below the Compound Nodular Band where the upper dark glauconitic clays give way to a lower browner group which are very reminiscent of D3 *sensu stricto*. Whichever interpretation of the D2–D3 boundary one adopts, Lamplugh's thicknesses are impossible to fit to the section seen today, but, neglecting his lithological statements, the " fit " is somewhat better as regards thickness if one takes the base of D2 at the marked colour change 2 feet below D1. This is clearly the interpretation of Danford who speaks of " D2 which averages only about 2½ feet in thickness " (1906b, p. 105). Thompson (1928, p. 57) reiterates this, while Lamplugh quotes Danford's statement in his review of the Speeton Clays (1924, p. 16). While this might imply tacit acceptance of Danford's interpretation it seems certain that Lamplugh was unaware of the thickness of clays between this boundary and the ferruginous stony band at the top of D3. In fact at this time his interest seems to have been more in the problems of the upper beds of the Speeton Clay than in the apparently straightforward lower succession. Danford's reading of the D2–D3 junction raises another problem for it means that 12½ feet of clays must be assigned to " D3 ". This can be reduced to 8 feet by mistaking the top nodule bed for the bottom nodule bed (quite often they are not exposed at the same time) but from Danford's statements it is obvious that he was taking the correct lower boundary to D3. Why he fails to comment that " D3 " has three times the thickness assigned to it by Lamplugh is a mystery.

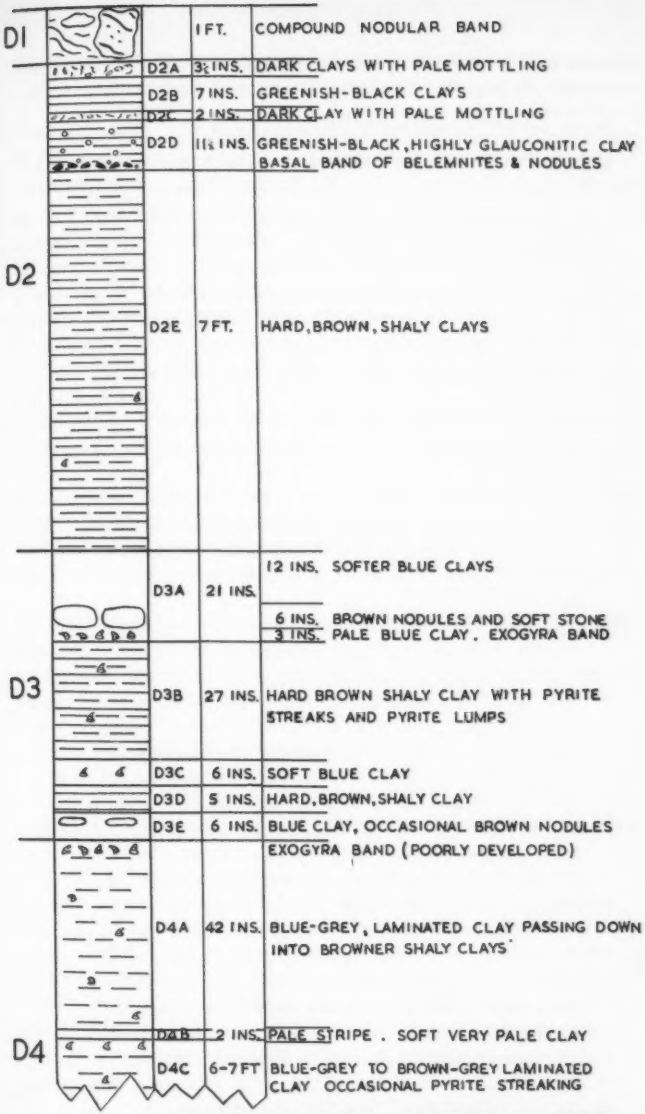
Lamplugh's subdivisions of the D Beds were largely based on lithological features and meant primarily for convenient reference in the field. Only later were the subdivisions fitted into the various Lower Cretaceous stages. Unless one put forward a completely new notation it would be a cardinal error to alter Lamplugh's boundaries to make the subdivisions coincide with the palaeontological divisions. Thus while Danford's boundary has everything to commend it from a palaeontological point of view the top of D3 must be defined in Lamplugh's original sense as long as Lamplugh's notation is retained. The top of D3 is, therefore, defined as lying just above the ferruginous nodular band or soft stone which forms one of the best marker bands in the D Beds. This band consists of rather large, flat, sometimes almost continuous brown nodules which occupy the lower part of a band of pale blue clay 21 inches thick. The actual boundary between D2 and D3 is taken at the top of this clay in which the nodules lie, at the point where the blue clay gives way to the overlying browner beds.

For ease of reference and accurate localization of material in the field, Lamplugh's various subdivisions have been further divided on lithological grounds by suffixing letters from the top downwards in conformity with that author's usage. This is shown in Text-fig. 2. The



UPPER D BEDS — LAMPLUGH 1889
WITH DANFORD'S BOUNDARIES OF 1906 ADDED

TEXT-FIG. 1.—Section through the Upper D Beds. Lamplugh 1889, fig. 4 (pars) re-drawn with Danford's boundaries of 1906 added.



UPPER D BEDS — SECTION 1960

TO THE SAME SCALE AS FIGURE 1.

TEXT-FIG. 2.—Section through the Upper D Beds—1960.

additional subdivision of the lower D Beds (D6–D8) will be covered in a paper dealing with the Berriasian ammonites from these beds.

NOTES ON THE SUBDIVISIONS RECOGNIZED IN THE UPPER D BEDS

The following notes are intended as a guide to the recognition of the various subdivisions in the field and are by no means exhaustive.

D1. 1 foot thick. The Compound Nodular Bed. Pale grey or bluish-grey nodules in dark clay. This bed is too well known to need further description and is perhaps the best of the six prominent marker bands in the Upper D Beds. It can usually be seen in the cliff where it weathers out as a line of large pale nodules although the development of the nodules is somewhat irregular and after heavy rain it has often been obscured and impossible to determine due to downwash. Recently it has been well exposed in the intertidal zone owing to the increased scour consequent on the destruction of the beach defence works noted above.

D2A. 3½ to 4 inches. Dark, strongly mottled clays. The mottling takes the form of pale grey ovals and streaks in a dark grey or black hard shaly clay. The mottling is on a smaller scale than that generally seen in D6 and D7 and is very reminiscent of that seen in C1.

D2B. 7 inches. Greenish-black glauconitic clays. This bed is intermediate between the highly mottled D2A and D2C. Sporadic mottling occurs and, but for the fact that the terminology set out here has been used for a considerable time in localizing the author's material, this division would not be recognized as a separate bed. D2A, D2B, and D2C may be linked together as " Upper D2 " or " the mottled beds ".

D2C. 2 inches. Dark clay with strong mottling.

D2D. 11½ inches. Greenish-black highly glauconitic clays. This is the most glauconitic part of D2 and commonly contains many black nodules. Lamplugh has commented on the angularity of many of these. The basal 2 inches is packed with belemnites belonging mainly to *Acroteuthis paracmonoides* Swinnerton and *A. acmonoides* Swinn. although other species also occur. These are often encrusted with glauconite and pyrite as well as with adherent foraminifera and small oysters suggesting the slow conditions of deposition postulated by many authors for the beds here classed as D2A–D2D. This basal bed was taken as the base of D2 by Danford (1906a, p. 6) who in connection with the belemnites noted that " at the very compact base of D2 they swarm ". This feature forms the second important marker band in the Upper D Beds.

D2E. 7 feet. Brown, shaly, sometimes rather streaky, clay. Large crushed *Polyptychites* occur in the upper part and smaller better preserved forms nearer the base. The top 18 inches is somewhat softer than the remainder, and whilst further subdivision might be made with detailed study, the whole 7 feet of clay is best treated as a single lithological unit. The clays are highly pyritic but glauconite is either entirely absent or quite insignificant, a feature which separates these beds from the rest of D2.

D3A. 21 inches. Softer blue clay the top foot of which contains flattened lamellibranchs and ammonites retaining the original shell. About 1 foot below the top is the nodule bed which forms a striking pale brown band in the cliff and foreshore exposures and which, after D1, is the best marker band in this part of the section. *Exogyra sinuata* occurs throughout the Upper D Beds but forms a very well defined band at the base of the nodules where the valves are often encrusted with *Serpulae*.

D3B. 27 inches. Hard, brown, shaly clay, showing thin streaks of pyrite on freshly broken surfaces. This bed yields a large fauna of all types of molluscs and *Serpula articulata*, the preservation of the fossils differing from those of the bed below in that they are not flattened, although the shell material is powdery or " mealy ".

D3C. 6 inches. Soft blue clay. Lamellibranchs are common, and while *Exogyra sinuata* is robust enough to retain its original form or yields by fracturing, the bulk of the fossils are flattened and retain the shell material in a fresher, harder form than those in the bed above.

D3D. 5 inches. Hard, brown shaly clay. This is similar to D3B, the fossils showing the same preservation, and indicates a return to the same conditions of deposition.

D3E. 6 inches. Occasional brown nodules in blue clay. These nodules are often flattened rather than round and are very similar to those of D3A. Very rarely are D3A and D3E clearly visible at the same time but the two beds are easily differentiated on thickness. The platy nodules in D3E average 2 or 3 inches in thickness, while those in D3A are twice this. This fourth marker band is much less prominent than D3A, and although there is also a band of *Exogyra sinuata* lying below these nodules it is very poorly developed and with difficulty distinguished from generally distributed specimens in the clays below. This bed forms the base of D3.

D4A. 41 inches–42 inches. Pale blue-grey laminated clays above, passing down into harder, browner, shaly clays. *Exogyra* and other fossils are common.

D4B. 2 inches. Very pale, soft clay. " The Pale Stripe ". This pale grey clay is an invaluable guide to the middle part of the D Beds, since in spite of its softness it is very often well exposed when the marker bands above are obscured. It provides a useful check against D3E when both beds are exposed.

D4C. 6 to 7 feet. Between D4B and D4D are about 7 feet of shaly or laminated clays which are predominantly brownish but which also contain blue-grey bands.

When clearly seen, as in stripped shore sections, the middle part of this division is strikingly studded with numerous belemnites and *Exogyra sinuata*, while fossils in the upper and lower parts of D4C appear much rarer in comparison.

D4D. 1 foot. Pale bluish-grey clay. The " soft slate coloured or brownish clay " of Lamplugh. This usually develops a rusty streak at its lower junction with D5, which serves as a useful marker.

D5. 6 to 7 feet. " The Lingula Bed ". Dark brown laminated clays with abundant pyrites, *Lingula ovalis* and belemnites. The latter show an abnormal preservation in that they are made of chalky white calcareous material, often stained with yellow or rusty tints, instead of being of hard crystalline calcite. The guards have a very weathered appearance and these phenomena are probably due to post-depositional changes involving the liberation of sulphuric acid due to the oxidation of the pyrites, the former attacking the calcite with concomitant formation of selenite. Whilst this may in part explain the poverty of the fauna, the fact that there is a very marked increase in the size of the lingulas in D4D suggests that this paucity is, in fact, due to inimical conditions at the time of deposition. Palaeoecological studies suggest that this bed was probably formed in very shallow water of rather restricted circulation, and the occurrence of nodules of coaly matter emphasize the rather unusual conditions. The thickness measured on the only occasion on which a clear section right through this bed has been seen gives about 6 ft. 6 in.— a slight increase on Lamplugh's measurements.

Good sections in lower D4C, D4D, and Upper D5 are rare and this group of clays is the least well exposed of the D Beds. When a good clean section across the D5–D4 boundary is seen, a most striking development of pyrite is visible in the top foot of D5 and in D4D. This takes the form of pyrite cylinders which lie at right angles to the bedding planes and show periodic constrictions. The tubes themselves are between an inch and a half and 3 inches long and about a quarter of an inch wide, and are obviously the pyritized burrows or holes of some marine

organism. They have not so far been noticed below the top foot of D5 or higher up in D4C which suggests that they are probably the burrows of a polychaete or some such organism, rather than *Lingula* which is very common in D4D and D4C and ranges down into the top 10 inches of D6 with sporadic occurrences both lower and higher in the section. The fact that this fossil is so common in D4C and D4D perhaps renders the term " Lingula Bed " for D5 somewhat misleading. It would be possible to divide D5 into two on the basis of these pyrite cylinders which are confined to the top foot, and it would be very easy to subdivide D4A and D4C. At present, however, any further subdivision would seem to serve no useful purpose.

Thickness

Lamplugh's measurements give a thickness of 34½ feet for the whole of the D Beds, whereas current measurements show the presence of between 44½ and 47 feet, which is nearer Judd's estimate as far as it is possible to tell from his sections. This may have an important bearing on the total thickness of the clays for while Lamplugh's *obiter dicta* on this subject (1924, p. 2) puts the thickness at " not much over 300 feet ", Judd (1868), suggests about 500 feet. If, as seems likely, Judd's estimate proves to be the more accurate this reduces the discrepancy between the thickness at outcrop and the thickness inland where the North Fordon G.1. bore-hole some seven miles W.N.W. of Speeton proved 695 feet of Speeton Clay (Neale 1960a, p. 203). On the other hand, this bore-hole lies to the west of the Hunmanby fault, a fact which may not be unconnected with the surprising thickness encountered.

Summary

1. The top of D3, and consequently the base of D2, is defined in accordance with Lamplugh's original definition and lies at the top of the clay band which contains a prominent band of brown, ferruginous nodules.
2. D2 and D3 are thicker than recorded by Lamplugh in his section (1889, fig. 4), the increase in thickness being some 30 per cent in the case of D3, and 125 per cent in the case of D2.
3. From a purely palaeontological point of view, Danford's placing of the D2–D3 boundary (at the junction of D2D and D2E of the present paper) is infinitely preferable to Lamplugh's.
4. Six main marker bands form the easiest guide to the Upper D Beds. In order of prominence these are : D1, D3A, D4B, D2D (base), D3B, and D4D.
5. Judd's estimate of the total thickness of the Speeton Clay will probably be found to be more nearly accurate than that of Lamplugh.

REFERENCES

BLAKE, J. F., 1891. The Geology of the Country between Redcar and Bridlington. *Proc. Geol. Assoc.*, xii, 115–144.

DANFORD, C. G., 1906a. Notes on the Belemnites of the Speeton Clays. *Trans. Hull Geol. Soc.*, vi (ii), 1–14.

—— 1906b. Notes on the Speeton Ammonites. *Proc. Yorks. Geol. Soc.*, xvi, 101–114.

JUDD, J. W., 1868. On the Speeton Clay. *Quart. Journ. Geol. Soc.*, xxiv, 218–250.

LAMPLUGH, G. W., 1889. On the Subdivisions of the Speeton Clay. *Quart. Journ. Geol. Soc.*, xlv, 575–617.

—— 1924. A Review of the Speeton Clays. *Proc. Yorks. Geol. Soc.*, xx, 1–31.

LECKENBY, J., 1859. Notes on the Speeton Clay of Yorkshire. *The Geologist*, ii, 9–11.

NEALE, J. W., 1960a. Marine Lower Cretaceous Ostracoda from Yorkshire, England. *Micropaleontology 6* (2), 203–224.

PAVLOW, A. and LAMPLUGH, G. W., 1892. *Argiles de Speeton et leurs équivalents.* Moscow.

SPATH, L.F., 1924. On the Ammonites of the Speeton Clay and Subdivisions of the Neocomian. *Geol. Mag.*, lxi, 73–89.

THOMPSON, C., 1929. The Speeton Clays and their Southern Equivalents. *Trans. Hull Geol. Soc.*, vii (ii), 41–69.

GEOLOGY DEPARTMENT,
THE UNIVERSITY,
HULL.

On the Tectonic Environment of Basic Magma

By Germaine A. Joplin

Abstract

An attempt has been made to show that basic magma is associated with vertical and not with folding movement, that basic intrusions take the form of those characteristic of unfolded regions and of relatively high levels and that differentiation *in situ* is common.

It is argued that basic magma is emplaced in the orogenic belts as flows and typically non-orogenic intrusions during the geosynclinal or sinking phase of the orogenic cycle, that rocks of the appinitic suite, which commonly occur as stocks associated with granodiorites, are formed from these non-orogenic basic rocks by a process of hybridization during a subsequent folding phase, but that no further basic magma is introduced during this phase.

It is suggested that the terms Non-orogenic Association and Orogenic Association might replace Volcanic Association and Plutonic Association to indicate the relation of basic and acid magmas to their tectonic environment.

Introduction

Most geologists agree that the Earth's surface may be divided broadly into three tectonic regions—ocean basins, continents and orogenic belts. Further, it is generally conceded that a rough correlation may be made between igneous rock-type and tectonic region; thus olivine basalts and their alkaline differentiates appear to predominate in oceanic regions, tholeiites in continental regions, and granites, granodiorites and members of the andesitic suite in orogens. Since oceans and continents occupy relatively stable areas, subjected mainly to vertical movements alone, and orogenic belts are disturbed areas, subjected to both folding and vertical movements, the above correlation presupposes some relation between non-orogenic areas and basic magma.

Le Verrier (1888) was probably the first to point out the association of basic magma with periods of stability and of acid with crustal movement when he stated, "En gros, les éruptions basiques paraissent coincider avec des périodes de calme et de sédimentation, tandis que les roches acides marquent des époques de grands movements et accompagnent des discordance d'étages géologiques." Though many petrologists have since related different rock-suites to different tectonic conditions, the correlation has been concerned especially with the differentiation of alkaline rocks, and the early and important concept of Le Verrier has received little attention, although Bucher (1933) pointed out the association of basic rocks with the sinking phase of the geosyncline and the current idea regarding the distribution of olivine basalt and tholeiite is suggestive.

It is obvious that the bulk of the basic rocks occur in the relatively

stable oceanic and continental areas and are associated only with vertical movement; nevertheless, basalts and basic intrusions also occur in the orogenic belts, and it is the purpose of the present paper to examine these occurrences in an attempt to ascertain whether they may be correlated with vertical movement as suggested by Le Verrier and by Bucher.

Rock-type and Intrusive Form

Benson (1926), in discussing the relation between tectonic conditions and the intrusion of basic and ultrabasic magma, divided basic intrusions into four classes:—

1. Laccomorphic Type (no dominant lateral pressure).
2. Cordilleran Type (associated with orogenic movement).
3. Alpine Type (associated with orogenic movement, particularly with overthrusting).
4. A type in the form of lenticular masses conforming to the structure lines of the country rocks, and possibly related to the cordilleran or alpine types.

The laccomorphic type includes the great layered intrusions which occur in the stable continental areas and have been classed by Kennedy and Anderson (1938) as members of the Volcanic Association. In the cordilleran type, Benson places the basic and ultrabasic members of the plutonic complexes (sometimes referred to as the appinitic suite), as well as the basic dyke swarms and minor intrusions which normally follow granitic intrusions, and in the alpine type he places the " green rocks " of Suess, or the " ophiolitic rocks " of Steinmann, which include the peridotite-serpentinite association (Turner and Verhoogen, 1951), as well as members of the spilitic suite.

The forms of igneous intrusions are a guide to the depth of burial and to the tectonic conditions obtaining at the time of their emplacement, so it is pertinent to examine these in relation to Benson's fourfold classification.

Non-orogenic Regions.

Benson's laccomorphic class refers to intrusions that take the form of laccoliths, lopoliths, sills, ring-dykes, cone-sheets, and other funnel-shaped bodies. Tyrrell (1926) classified these forms as characteristic of unfolded regions, and the fact that they commonly show perfect crystal layering also suggests that they have crystallized under tranquil, stable conditions. In most cases the intrusive mechanism is by doming overlying sediments or by cauldron subsidence, both of which indicate relatively shallow burial.

Such forms are found in the continental and stable shield areas where they consist of basic and ultrabasic rocks associated with minor acid materials. Basic flows and dykes are also common in these areas.

The layered intrusions and flows of the non-orogenic areas consist of tholeiite or of olivine basalt. Tilley (1951) considers that olivine basalt is a differentiate of tholeiite, and prefers to refer to it as alkaline olivine basalt or plateau basalt. The differentiation trends of both these basaltic types have been fully documented in many detailed studies and it is known that the tholeiite gives rise to olivine-bearing ultrabasic rocks and gabbros, showing a progressive enrichment in iron as well as in alkalis and silica with the final production of a relatively small amount of granophyre, whilst the alkaline olivine basalt produces an olivine-rich ultrabasic rock and alkaline gabbros such as essexites, teschenites, and theralites with an acid alkaline residuum such as pantellerite, comendite or soda granite. Neither type gives rise to intermediate rocks like those occurring in the cordilleran intrusions.

Orogenic Regions.

According to Benson three classes of basic intrusion are associated with lateral movement, and therefore belong to the orogens—cordilleran and alpine types and a type which is rather ill-defined and may belong to either of the above. Nevertheless, flows and many laccomorphic forms occur among geosynclinal sediments, and it is concluded that these were emplaced under non-orogenic conditions during the sinking phase of the geosyncline.

In a recent paper Buddington (1959) states, " Most of the mafic rocks in the orogens are lava flows and intrusive diabase, dolerite or gabbro sheets emplaced under conditions of the epizone previous to major deformations."

As in the case of the non-orogenic regions many of the flows and laccomorphic intrusions in geosynclines consist of tholeiite or of alkaline olivine basalt and their differentiates, but laccoliths or ring-dykes of granite, diorite or syenite also occur in the orogenic belts. Flows and minor intrusions among geosynclinal deposits commonly consist of spilite.

In the plutonic complexes of Benson's cordilleran class large bathyliths of granodiorite are commonly associated with small satellitic stocks consisting of members of the appinitic suite which may include peridotite, pyroxenite, hornblendite, hornblende gabbro, monzonite and diorite. Formerly these rocks were considered to be early differentiates of a basic magma and co-magmatic with granodiorites and granites. Many petrologists now believe in the existence of independent basic and acid magmas, and although there is no concensus of opinion regarding the origin of the intermediate rocks, the present writer

(Joplin, 1959) has suggested a mechanism by which basic and ultrabasic rocks intruded or extruded during the building of the geosynclinal pile were shattered and hybridized at an early stage of, or just prior, to folding. Thus the basic magma was emplaced during the geosynclinal, non-orogenic phase, and though the appinitic stocks were formed subsequently no further basic magma was introduced.

Minor intrusions such as dykes of lamprophyre, dolerite and porphyrite were injected into granite and country rocks after the decline of the folding and are therefore also non-orogenic in origin.

Benson places the " green rocks ", which include spilites and certain dolerites and gabbros, with ultrabasic intrusions of the peridotite-serpentinite association in his alpine class, and points out that these rocks occur among geosynclinal sediments, commonly with cherts, and that all are pre-granite in origin, though the spilitic and basic rocks pre-date the peridotites.

The spilite suite consists mainly of albite-bearing basalt and dolerite associated with minor amounts of picrite at one end of the differentiation series and of quartz keratophyre at the other. These rocks occur as sills, dykes, and flows and many of the last show pillow structure indicating a submarine origin.

Ultrabasic intrusions of peridotite and of serpentinite on the other hand normally occur as steeply inclined sheets or as relatively small lenticular bodies, and all occurrences appear to be associated with thrusts. In the main these are concordant bodies, though small scale discordances are noted.

Like Benson, Turner and Verhoogen (1951) draw attention to the common field association of spilites and serpentinites and briefly discuss the possibility of the olivine-poor spilites being a complementary differentiate of peridotite. It is difficult to find a mechanism for such complementary separation, but it is tempting to suggest that basic sills or laccoliths, injected near the surface of the geosynclinal pile whilst it was still sinking, differentiated to form an ultrabasic layer, and that later, when these intrusions occupied a deep level, escaping water, released as a result of deep-seated metamorphism lubricated the ultrabasic differentiate so that it was squeezed along thrust planes at the onset of orogenesis and so isolated from its basic and acid differentiates. Prior to orogenesis, but because of their geosynclinal environment, the feldspar-bearing differentiates, together with flows and minor intrusions of the same composition, were altered to spilite and keratophyres, and futher alteration may have been brought about by the escaping fluids that lubricated the ultrabasic rocks. This suggestion regarding the origin of the spilites is not dissimilar from ideas advanced by Scott (1953) and by Waters (1955).

Whatever be the origin of the spilites it seems evident that they were

extruded or intruded during the quiet conditions of sedimentation, thus the basic magma comprising them may be correlated with vertical movement and non-orogenic conditions.

Hess (1938) suggested that the peridotites were derived by the melting of a deep-seated ultrabasic substratum and that an aqueous magma was brought up along thrust planes, but as pointed out by Turner and Verhoogen the existence of such a magma is not in accord with experimental facts. Nevertheless, the possibility of a very deep-seated origin cannot be dismissed, for by some mechanism it might be possible for a part of the ultrabasic substratum to be squeezed up as a solid, cold intrusion during deep seated thrusting.

If a geosyncline is subjected to more than one orogeny, it seems likely that small lenses of serpentine may be detached from larger underlying intrusions emplaced during the first major orogeny (Hess, 1940) and that these may move along thrust planes as solid masses during the later minor orogenies.

The origin of the serpentinites and peridotites must be left an open question. If they should be ultrabasic differentiates of spilite then their origin is non-orogenic ; if on the other hand they are derived from an ultrabasic substratum and not from an original basic magma, they may be correlated with orogenesis, particularly with overthrusting, and the question of the basic magma's being related to such a movement does not arise. Thus, whatever be the origin of the ultrabasic intrusions, there seems reason to believe that basic magma is associated with vertical movement only and not with lateral compression.

Benson erected a fourth class of basic intrusions which is not well defined, but it seems to the present writer that these are masses which have suffered a deformation subsequent to emplacement, and that they may have been injected as tabular concordant bodies that have since been folded. Many masses of amphibolite possibly belong to this category.

Non-orogenic and Orogenic Associations

Although Kennedy and Anderson (1938) recognized that " the problems of igneous activity are inseparably linked with those of geophysics on the one hand and crustal tectonics on the other ", they chose the rather misleading terms " Volcanic Association " and " Plutonic Association " to distinguish the two great groups of rocks that characterize non-orogenic and orogenic regions, so that their tectonic significance is to some extent obscured.

These authors pointed out that the " Volcanic Association " is characterized by basic rocks, and because of their composition and association with volcanic provinces the great layered basic plutonic intrusions are included as " accidental " intrusions. The andesitic

lavas, which occur in the orogens and have close chemical and mineralogical affinities to the plutonic rocks of the same environment, are also included in the " Volcanic Association ", partly for the reason that they are lavas, but also because it was thought that they had a basaltic parentage.

Whilst it is recognized that Kennedy and Anderson's subdivision is of the utmost importance, a subdivision on a tectonic basis would appear more useful, and the writer suggests the terms " Non-orogenic Association " and " Orogenic Association ". The Non-orogenic Association would include all basic rocks and their differentiates that are intruded or extruded in the oceanic or continental regions or in the orogens during the geosynclinal, sinking phase, and would therefore correspond to the " Volcanic Association " with the exclusion of the andesites. The Orogenic Association would include all rocks of the " Plutonic Association " with the addition of the andesites. As the appinite suite is related to the more acid plutonic rocks in place and in time and since hybridization of the earlier non-orogenic basic rocks takes place only as a result of the orogeny, these plutonic rocks should remain with other plutonic rocks of the " Orogenic Association ".

REFERENCES

Benson, W. N., 1926. The Tectonic Conditions accompanying the Intrusion of Basic and Ultrabasic Igneous Rocks. *Mem. Nat. Acad. Sci.* 1, xix, 1—89.

Bucher, W. H., 1933. *The Deformation of the Earth's Crust.* Princeton University Press.

Buddington, A. F., 1959. Granite Emplacement with Special reference to North America, *Bull. Geol. Soc. Amer.*, lxx, 736.

Hess, H. H., 1938. A Primary Peridotite Magma. *Amer. Journ. Sci.*, xxxv, 321—344.

———, 1940. Appalachian Peridotite Belt. Its Significance in Sequence of Events in Mountain Building. *Abstr. Bull. Geol. Soc. Amer.*, li, 1996.

Joplin, G. A., 1959. On the Origin and occurrence of Basic Bodies associated with Discordant Bathyliths. *Geol. Mag.*, xcvi, 361–373.

Kennedy, W. Q., and E. M. Anderson, 1938. Crustal Layers and the Origin of Magmas. *Inter. Geophy. Union Bull. Volc.*, ii, 3.

Le Verrier, M., 1888. Note sur les Causes des Mouvements Orogeniques *Bull. Soc. Geol. France, 3rd Ser.*, xvi, 498.

Scott, B., 1953. The Metamorphism of the Cambrian Basic Volcanic Rocks of Tasmania and its Relationship to Geosynclinal Environment. *Proc. Roy. Soc. Tasmania*, lxxxviii, 129–149.

Tilley, C. E., 1951. Some Aspects of Magmatic Evolution. *Quart. Journ. Geol. Soc.*, cvi, 37–61.

Turner, F. J. and J. Verhoogen,1951. *Igneous and Metamorphic Petrology.* New York, p. 247.

Tyrrell, G. W., 1926. *The Principles of Petrology.* London, pp. 17–26.

Waters, A. C., 1955. Volcanic Rocks and the Tectonic Cycle. *Geol. Soc. Amer. Spec. Paper*, lxii, 703—722.

Department of Geophysics,
Australian National University,
Canberra.

The Feeding Mechanisms of Spire-bearing Fossil Brachiopods

By M. J. S. Rudwick

Abstract

The lophophores of spire-bearing fossil brachiopods (Spiriferoidea and Atrypoidea) are reconstructed by homological comparison with living brachiopods. It is inferred that all spiral brachidia supported simple spiral lophophores. For each type of brachidium, only one arrangement of the spirolophe could have created an efficient filter-feeding system. The water would have entered the mantle cavity laterally and been ejected medially ; but would have been filtered between the whorls of the conical spiralia either outwards (e.g. *Atrypa*) or inwards (e.g. *Spirifer*). These are the only possible alternatives : it is probable that both systems were evolved more than once.

I. Relation of Brachial Axes to Brachidium

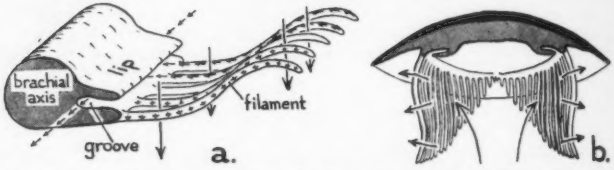
The calcareous spiral ribbons (*spiralia*) enclosed between the valves of atrypoid and spiriferoid brachiopods have long been interpreted as the supporting structures of spiral lophophores (*spirolophes*). Orton, who studied the spirolophe of *Crania* (1914), suggested that the feeding mechanism of the fossil genera might have been similar. The purpose of this paper is to examine this suggestion in greater detail, in the light of more recent evidence on the feeding mechanisms of living brachiopods.

The lophophore is bilaterally symmetrical. On either side of the median plane, where the mouth is situated, a linear arm or *brachium* extends laterally to a terminal growing point. The brachia are variously looped or coiled and attached in varying degrees to the body-wall and dorsal mantle surface. Thomson (1927) termed the linear axis of the brachium the " body of the lophophore " ; but this is rather ambiguous, and *brachial axis* is suggested instead (Text-fig. 1 (*a*)). Along the brachial axis runs a food-groove leading to the mouth, bounded on the *frontal* side by a *lip* and on the *abfrontal* side by a ridge from which the *filaments* (*cirri* or *tentacles* of some authors) spring. The filaments are long, slender, and flexible ; and they lie essentially in a single row along the axis (alternate filaments are generally differentiated into two series, one slightly closer to the food-groove than the other ; but this will not affect the present discussion).

The reconstruction of the brachial axes on their skeletal supporting structure (the *brachidium*) is the first step in the reconstruction of the feeding mechanisms of the fossil genera. Williams (1956) postulates that the spiral brachidia of spiriferoids (Text-fig. 2 (*c*1)), despite their apparent similarity to simple spirolophes, in fact supported doubled loops of the brachial axis, with the tips of the brachia lying close

together on the jugum (Text-fig. 2 (*c*2)). Such loops would be homologous to the lateral arms of a plectolophe (Text-fig. 3 (*a*)). Then the development—in morphological series—of a forked jugal process, a pair of accessory lamellae (e.g. *Athyris*) and ultimately a second pair of spiral ribbons running closely parallel to the first (e.g. *Diplospirella* : Text-fig. 2 (*d*1)), is taken to represent the migration of the tips of the brachia away from the jugum, and hence a further lengthening of the brachial axes. Thus genera with double spirals are reconstructed with *three* loops of the brachial axis spiralling in parallel (Text-fig. 2 (*d*2)).

These reconstructions seem to be based on the assumption that there



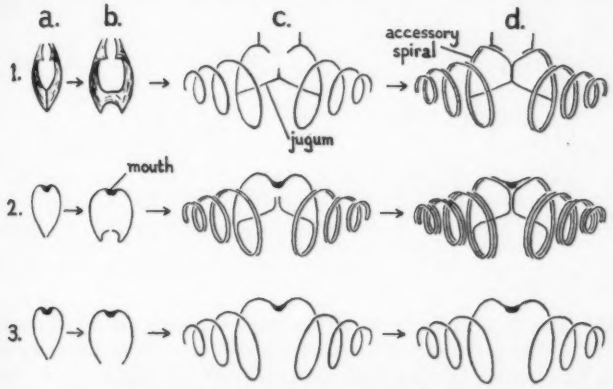
TEXT-FIG. 1.—(*a*) Diagram of a short section of the left brachium of *Tegulorhynchia*, to illustrate the basic structure and mode of action of the lophophore. The direction of action of the lateral cilia is shown by broad arrows on the nearest two filaments ; and the water-currents they produce, by long arrows between the filaments. On the furthest two filaments the normal action of the frontal cilia is shown ; and in the groove, the ciliary current leading towards the mouth.

(*b*) Diagram of a dorsal valve with sessile trocholophe, cut transversely and viewed from posterior side : to show orientation of filaments. Shell, black ; stippled area represents mantle tissue, visceral cavity and brachial axes (which in this case are sessile on the mantle).

was a close relation between the course of the brachidial lamellae and the course of the brachial axes; and, more specifically, that the brachial axes extended on to the jugum. But the variety of structures that support the plectolophes of Recent brachiopods shows that, in these genera at least, there is no such close relation and that some parts of the brachidium have no connection with the brachial axes (Text-fig. 3). This follows naturally from the fact that the brachidial lamellae are in no sense embedded in, or calcifications of, the lophophore itself. They are extensions of the dorsal valve, sheathed with epithelium continuous with that lining the dorsal valve (as Williams has noted). They support the lophophore externally at certain points but are wholly distinct from it. They are not, as Hyman (1959) appears to assume, " inside " the lophophore.

Therefore, the jugum of spiriferoids, like the bands connecting the loop to the septum in *Terebratella* (Text-fig. 3 (*c*)), might not have borne any part of the brachial axes. Williams' assumption that it did derives

from his interpretation of the early growth-stages of the brachidium of genera such as *Zygospira*. If the early simple loop (Text-fig. 2 (*a*1)) bore a trocholophe, the tips of the brachia would have been close together at the tip of the loop (Text-fig. 2 (*a*2)). At a later stage the tip splits and the loop is modified into a pair of prongs joined by a transverse band (Text-fig. 2 (*b*1)). Williams assumes that the tips of the brachia would have remained close together, i.e. on the transverse band (Text-fig. 2 (*b*2)). But there is no evidence for this: they might have diverged, remaining on the tips of the prongs (Text-fig. 2 (*b*3)). Since

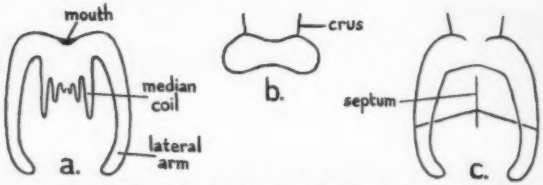


TEXT-FIG. 2.—Diagram to show inferred relations of lophophore to brachidia in spiriferoids. (1) the brachidium (lamellae represented as lines in *c* and *d*); (2) the lophophore as reconstructed by Williams (interpreted from Williams, 1956); (3) the lophophore as reconstructed here: arrangement of lophophore shown by line representing course of food-groove (filaments, etc. omitted). (*a*, *b*) early stages in ontogeny; (*c*) " normal " spiriferoid (without accessory lamellae); (*d*) spiriferoid with double spiral lamellae (e.g. *Diplospirella*).

the prongs ultimately develop into the spiralia and the transverse band into the jugum, Williams' interpretation of the adult brachidium follows logically from his interpretation of this early growth-stage. But on the alternative interpretation the adult brachidium would have borne a simple spirolophe (Text-fig. 2 (*c*3)); and the development of double spirals would have represented not a fundamental modification of the lophophore but merely the acquisition of an additional supporting structure (Text-fig. 2 (*d*3)). This is more in accord with the known relation between lophophores and brachidia in living brachiopods than the interpretations suggested by Williams; it leaves open the question of the relations and function of the jugum.

II. Orientation of Brachial Filaments

The mode of action of the lophophore is now known in representatives of almost all the groups that have survived to the present day—*Lingula* (Chuang, 1956), *Crania* (Orton, 1914, Atkins (unpublished)), *Tegulorhynchia* (Rudwick (unpublished)), *Terebratulina* (Atkins, 1956), and several terebratelloids (Richards, 1952, Atkins, 1956, 1958, 1959 (*a*), and unpublished). It seems to be essentially uniform throughout the phylum * (Text-fig. 1 (*a*)). Lateral cilia, lying along the lateral surfaces of each filament, beat across the length of the filaments and thereby draw water through the row of filaments from the frontal to the



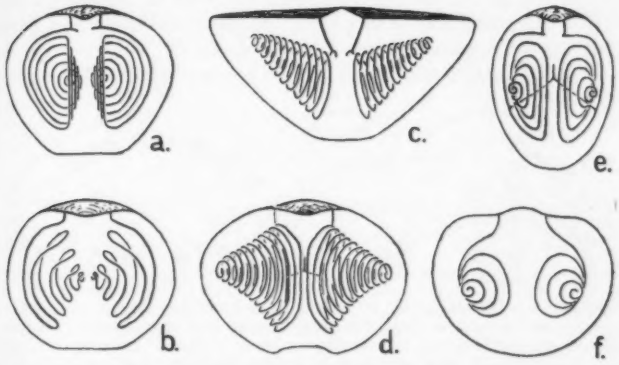
Text-fig. 3.—Diagram to show relation of a plectolophe (*a*) to its supporting structures in living brachiopods, (*b*) to a "short loop" (*Terebratulina*), (*c*) to a "long loop" (*Terebratella*). Conventions as in Text-fig. 2.

abfrontal side. Particles are caught out of this water current on to the frontal surfaces of the filaments and conveyed by frontal cilia either to the food-groove (along which they are borne by other cilia to the mouth) or to the tips of the filaments (whence they are ultimately rejected from the mantle cavity). Thus the lophophore acts as a combined pump and filter ; and its direction of action is always from the frontal to the abfrontal side of the brachia.

Orton remarked on the striking similarity, in both structure and mode of action, between the lophophores of brachiopods and the filter-feeding organs of many animals in other phyla. Pantin (1951) has pointed out that this detailed convergence is governed by the rigid mechanical specification to which any filter-feeding mechanism must conform for functional efficiency. Thus the assumption that the lophophores of extinct brachiopods possessed essentially the same structure and mode of action as those of living brachiopods is supported not merely on grounds of systematic affinity but also on grounds of functional necessity.

* Richards' account of *Neothyris lenticularis* differs so markedly from all the others that Atkins (1956) has suggested that it may have been based on specimens in which the lophophore was functioning abnormally. I have re-studied this species, and also *Terebratella inconspicua* and *T. sanguinea*, which Richards used as supplementary material, and have found that the lophophore corresponds to those of the species described by Atkins.

In the early stages of ontogeny the lophophore has the simple trocholophous form. The filaments have a bell-like arrangement and the axes of the brachia form a circle or crescent on the body-wall and dorsal mantle. The frontal sides of the brachia face inwards, so that water is filtered from the inside of the " bell " to the outside (Text-fig. 1 (*b*); cf. Atkins, 1956). This orientation could be expressed alternatively by stating that, when looking along the row of filaments



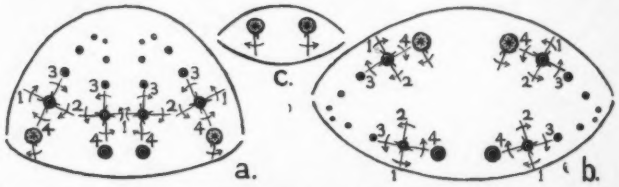
TEXT-FIG. 4.—Some spiral brachidia, viewed from ventral side: showing division into an " *Atrypa*-group " (*a*, *b*) and a " *Spirifer*-group (*c–f*) on basis of direction of coiling ; also showing " moulding " of brachidium to form of shell. (*a*) *Atrypa reticularis* ; (*b*) *Glassia obovata* ; (*c*) *Spirifer striatus* ; (*d*) *Meristina tumida* ; (*e*) *Dayia navicula* ; (*f*) *Koninckina leonhardi*. Based on specimens in the Sedgwick Museum, but slightly idealized (and lamellae represented as single lines) in order to clarify perspective.

towards the tip of the brachium, the filaments of the left brachium filter in a clockwise direction (taking the brachial axis as the centre of reference) and those on the right brachium filter in an anti-clockwise direction. Since all the more complex forms of lophophore are derived from the trocholophe during ontogeny merely by the lengthening, twisting, and coiling of the brachial axes, the same relation necessarily holds for all types of lophophore.

In *Atrypa* the apices of the spiralia are directed dorsally; in *Spirifer*, laterally. But the difference is more fundamental than this might suggest, for no change in orientation alone can transform (morphologically) an *Atrypa* into a *Spirifer*. Looking up the left spiralium from the base towards the apex, the lamella is coiled anti-clockwise in *Atrypa* and clockwise in *Spirifer*; and *vice versa* for the right spiralium (Text-fig. 4 (*a*, *c*). Hence an *Atrypa* can be transformed into a *Spirifer* only by turning the spiralia inside out, i.e. through an intermediate

with plane spiralia. On this criterion all other spire-bearing genera fall into one category or the other: for example, *Glassia*, with medially directed spiralia, can be classed with *Atrypa*; and *Koninckina*, with ventrally directed spiralia, with *Spirifer* (Text-fig. 4 (*b*, *f*)). Morphological transformations *within* either the "*Atrypa*-group" or the "*Spirifer*-group" depend only on changes in proportion and orientation of the spiralia. (It is unfortunate that these groups do not correspond to the present taxonomic divisions of Atrypoidea and Spiriferoidea (see Muir-Wood, 1955): for example the atrypoid *Dayia* (Text-fig. 4 (*e*)), belongs to the "*Spirifer*-group").

If the spiralia of *Atrypa* and *Spirifer* are reconstructed bearing the

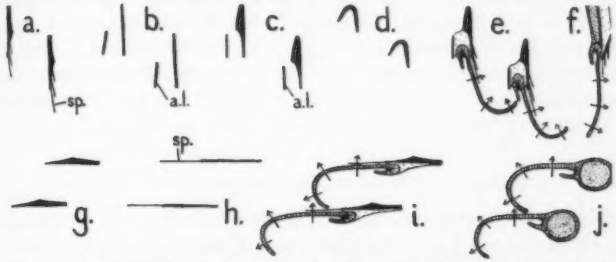


TEXT-FIG. 5.—Diagrammatic transverse sections of (*a*) *Atrypa*, (*b*) *Spirifer*, and (*c*) a common early growth stage with trocholophe. Sections of brachial axis represented as black circles. The most proximal section of each brachium is distinguished by an asterisk, and has one possible orientation of the filaments (and direction of filtering) marked: compare these sections with Text-fig. 1(*b*). The sections of the brachia representing the second whorl are marked with four alternative possible orientations of the filaments (1–4).

brachial axes, then the filaments might have projected from the axes in any direction—allowing for possible twisting of the axes. But nevertheless the orientation of the frontal and abfrontal sides of the filaments would have been governed by the rule derived above. In Text-fig. 5, one whorl of each brachium is shown with four of the possible orientations: no amount of twisting of the brachia could have produced the converse orientations.

There is some evidence to suggest that the filaments projected outwards, away from the axis of the spiral. The spiralia of several spire-bearing species (e.g. *Spiriferina rostrata*, *Athyris planosulcata*, and *Atrypa marginalis*: see figures in Davidson, 1851–86) bear slender irregular spines, which closely resemble those on the anterior tips of the loops of several Recent terebratelloids. In the latter the spines project forwards from the anterior edge of the lamella and from its median-facing side; and the abfrontal side of the brachial axis lies against the *other* side of the lamella, with the filaments projecting, in their proximal portions, roughly parallel to the spines (Text-fig. 6 (*f*)). The spines and the brachial axis have this same relation throughout

ontogeny (see Atkins' figures of *Macandrevia* (1959 (*b*), fig. 5, 6, 8)). In the spiriferoids cited above, the spines project from the outer edge of the lamella and from its *basal* side (facing the base of the spiralium) (Text-fig. 6 (*a*)): hence by homology the abfrontal side of the brachial axis probably lay against the *apical* side (facing the apex of the spiralium), with the proximal portions of the filaments projecting outwards (Text-fig. 6 (*e*)). In *Atrypa marginalis* too the spines project



TEXT-FIG. 6.—Reconstructions of brachia on spiral lamellae. (*a–c*) Sections of two adjacent whorls of lamella in spiriferoids ; outer edge of lamella pointing downwards, base of spiral towards right (*a*) *Spiriferina rostrata ;* (*b*) *Diplospirella* sp. ; (*c*) *Kayseria lens*); (*d*) Lamellae of *Thecospira* sp. in same orientation; (*e*) Composite reconstruction of brachium of *Spirifer*-group ; sections of two adjacent whorls in same orientation; (*f*) Horizontal longitudinal section of anterior end of lateral arm of *Macandrevia*, showing relation of brachial axis to spines on loop (median plane towards right); (*g–h*) Sections of two adjacent whorls of lamella in atrypoids; outer edge of lamella towards left, base of spiral towards foot of page ((*g*) *Atrypa reticularis*; (*h*) *A. marginalis*); (*i*) Composite reconstruction of brachium in *Atrypa*-group; sections of two whorls in same orientation; (*j*) Corresponding sections of brachium of *Tegulorhynchia.*

a.l., accessory lamella ; *sp.*, spines on lamellae; brachial axis and filaments hatched, with direction of filtering shown; great brachial canal closely stippled; brachial pouch lightly stippled; epithelia sheathing lamellae and spines omitted; scale not uniform. (*b*, *d* after Bittner, 1890; *c*, *h* after Davidson, 1851–86; remainder original).

outwards, though it is not clear whether they occur on either side of the lamella (Text-fig. 6 (*h*)). In Text-fig. 6 (*i*), the brachial axis of *Atrypa* is provisionally placed against the basal side of the lamella (which is presumably homologous to the apical side in the *Spirifer*-group).

In spiriferoids with double spirals, the accessory lamella lies near the apical side of the main lamella; that is, on the same side as the putative position of the brachial axis. This fact, and more especially the form of the two lamellae in *Kayseria* (Text-fig. 6 (*c*)), suggests that the brachial axis was probably sandwiched between the lamellae, the

accessory lamella thus acting as an accessory supporting structure (Text-fig. 6(*e*)). The unique grooved lamella of *Thecospira* (Text-fig. 6 (*d*)) could have housed the brachial axis in the same orientation.

This evidence suggests that the brachial axis lay against the apical side of the lamella in the *Spirifer*-group, and against the basal side in the *Atrypa*-group; and that in both groups the proximal portions of the filaments projected outwards, away from the spiral axis (Text-fig. 6 (*e*, *i*). In these reconstructions it is assumed (*a*) that the great brachial canal is a hydrostatic "skeleton" functionally equivalent to a brachidial lamella and was, therefore, not represented in the brachial axes of spire-bearing genera; and (*b*) that the brachidial lamella was accompanied, as in living genera, by a brachial pouch: the validity of these assumptions does not affect the main argument of this paper).

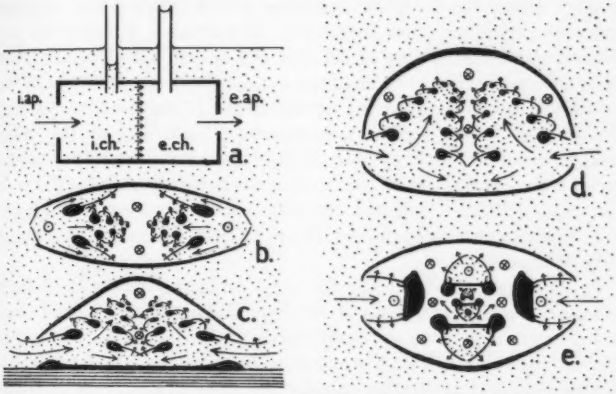
III. Organization of Filter-feeding Current-systems

As Hancock (1858) pointed out, the lengthening of the brachia and increasing complexity of the lophophore during ontogeny must reflect an increasing capacity to collect food particles. But the lophophore would be highly inefficient if the brachia and filaments were coiled at random within the mantle cavity. The essential character of any efficient filter-feeding system is that water which has been filtered should be prevented from passing through the filter again; or, in other words, that the filtered water should be strictly separated from the unfiltered. If the filter is placed within an effectively enclosed space, it is then necessary for the space to be divided by the filter into *inhalant* and *exhalant* chambers, with separate *inhalant* and *exhalant apertures* (Text-fig. 7 (*a*)). Any such arrangement of chambers, apertures, and consequent water-currents will be termed a *current-system*.

This specification applies to *any* filtering system within an enclosed space. It is, therefore, not surprising to find that it is fulfilled in the arrangement of the filtering organs of many diverse filter-feeding animals, such as most lamellibranchs, filter-feeding gastropods and ascidians. It applies also to all living brachiopods in which the filtering systems are known * (Text-fig. 7 (*b–e*)). The filaments are always arranged in certain definite positions. Their tips touch either the

* Orton figured the brachia of *Crania* tightly coiled and the filaments of all the whorls projecting outwards; and hence inferred a current-system with inefficient repeated filtering. The orientation figured here is that found by Atkins (unpublished). Chuang (1956) figures the filaments of the "minor spirals" of *Lingula* projecting outwards like those of Orton's *Crania*. This is the position assumed when the filaments have relaxed only partially, after forcible opening of the shell. In undisturbed specimens viewed through the median exhalant aperture while in the act of feeding, or in opened specimens that have been allowed to relax completely, the filaments are flexed into the position figured here.

mantle surface or edge (sometimes projecting beyond the edge), or the brachial axis on another part of the brachium, or the tips of the corresponding filaments on the other brachium; or else they project freely at the gape between the valve-edges, dividing the gape into inhalant and exhalant apertures. Only in this way can the filaments and brachial axes together divide the mantle cavity into separate chambers and so produce an efficient current-system. Hence the



TEXT-FIG. 7.—(*a*) Diagram of an ideally efficient filter-feeding current-system, showing pump/filter separating inhalant chamber (*i.ch.*) from exhalant (*e.ch.*), with inhalant and exhalant apertures (*i.ap.*, *e.ap.*). " Manometers " indicate pressure-changes across the system. (*b–e*) Filter-feeding current-systems of living brachiopods, shown in transverse sections: (*b*) *Lingula* spp. (based on Chuang, 1956, with modifications); (*c*) *Crania anomala* (based on Atkins (unpublished)); (*d*) *Tegulorhynchia nigricans* (original); (*e*) *Terebratella inconspicua* (original). Shell, mantle, and brachial axes, solid black; filaments shown with directions of filtering; general directions of water-currents shown by larger arrows for currents in plane of section, by cross-in-circle symbols for currents flowing anteriorly, and by dot-in-circle symbols for currents flowing posteriorly ; unfiltered water stippled; filtered water (i.e. exhalant chamber) unstippled ; substratum omitted except in *c* ; scale not uniform.

supposition that the filaments were similarly arranged in extinct brachiopods is supported not only on homological grounds, but also on grounds of functional necessity. On this criterion it is difficult to see how the lophophores of spiriferoids as reconstructed by Williams could, for all their wealth of filaments, have produced any workable current-system.

Of the four possible orientations of the filaments shown in Text-fig. 5 for *Atrypa* and *Spirifer*, positions 1 and 2 (filaments projecting freely) would thus have given highly inefficient filtering systems unlike

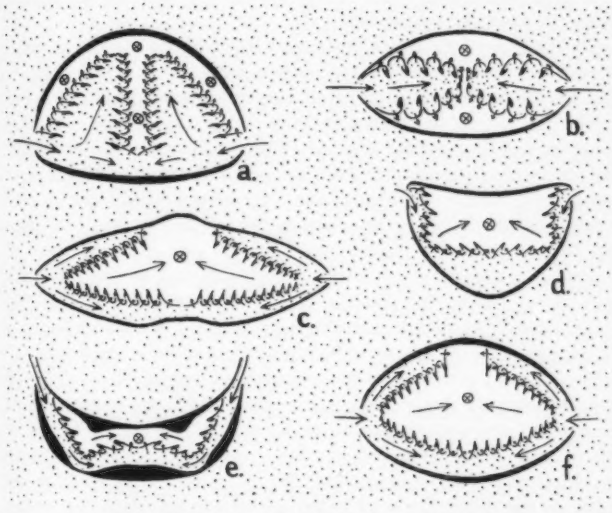
that of any known living brachiopod. In positions 3 and 4, on the other hand, each brachium would have formed a cone in which the gaps between the whorls of the brachial axis were bridged by the filaments, forming an unbroken wall. But in position 3, the filaments of the first (proximal) whorl would have touched the brachial axis of the second whorl, and no filaments would have been available to bridge the gap between the mantle surface and the brachial axis of the first whorl. Hence the complete separation of the inhalant and exhalant chambers would have been impossible. In position 4, however, the gap between the brachial axes of the first and second whorls would have been covered by the filaments of the second whorl, leaving those of the first whorl free to complete the separation of the chambers by touching the mantle surface or the corresponding filaments on the other brachium. (No " leakage " would have occurred at the apex of the cone, if the extreme tip of the brachium was tightly coiled, as it is in the spirolophes of *Crania* and *Tegulorhynchia*.) Thus position 4 is the only possible orientation by which an efficient filtering system could have been achieved.

If, as suggested above, the filaments projected outwards in their proximal portions, their distal portions must, therefore, have been flexed frontally in *Atrypa* and abfrontally in *Spirifer*, so that their tips touched the axis of the next proximal whorl (Text-fig. 6 (*e*, *i*); 8 (*a*, *c*)). Similar flexure occurs in the spirolophes of living brachiopods (Text-fig. 7 (*b–d*)). On the proximal whorl the filaments must have touched the body-wall or mantle surface, or the tips of the corresponding filaments on the other brachium (those on the anterior side of this whorl would have straddled the gape between the valve edges and delimited the apertures).

Thus for each type of brachidium only one possible efficient current-system can be derived. In *Atrypa* the water would have been drawn into the mantle cavity laterally and antero-laterally, and thence up the interior of the spirals. It would have been filtered while being drawn outwards through the filaments into the exhalant space outside the spirals; and would have emerged from the mantle cavity in a current flowing forwards through a median exhalant aperture (Text-fig. 8 (*a*)). This current-system is identical with that of *Tegulorhynchia* and almost identical with that of *Crania* (Text-fig. 7 (*d*, *c*)). Since the spirals would have contained inhalant (unfiltered) water, this will be termed an " inhalant " spirolophous current-system.

In *Spirifer* the frontal surfaces of the filaments must have faced outwards. Therefore the water would have been filtered by being drawn through the filaments *inwards* into the interior of the spirals, having previously entered the mantle cavity laterally and antero-laterally as in *Atrypa*. After filtering it would have flowed down the

interior of the spirals to their bases, emerged there and flowed forwards as a median exhalant current through a median aperture (Text-fig. 8 (*c*)). Since the spirals would have contained exhalant (filtered) water, this will be termed an "exhalant" spirolophous current-system. This differs from the system of apertures suggested by Orton for *Spirifer*, for he assumed that the direction of flow relative to the spirals would have been as in *Crania* and, therefore, inferred that the arrangement



TEXT-FIG. 8.—Reconstructions of filter-feeding current-systems of spire-bearing fossil brachiopods, shown in transverse sections: (*a*) *Atrypa reticularis*; (*b*) *Glassia obovata*; (*c*) *Spirifer striatus*; (*d*) *Dayia navicula*; (*e*) *Koninckina leonhardi*; (*f*) *Meristina tumida*. Symbols and conventions as in Text-fig. 7.

of the apertures would have been reversed (i.e. a median inhalant aperture and paired lateral exhalant apertures). But by the preceding argument the filaments of *Spirifer* cannot have had the same orientation as those of *Crania*; and, therefore, while the direction of flow relative to the spirals must have been reversed, the arrangement of the apertures must have been the same.*

When similar reasoning is applied to other spire-bearing genera, it is clear that all members of the *Atrypa*-group must have had inhalant

* Orton also suggested that the lateral alae on some spiriferoid shells could have acted as exhalant siphons comparable with those of lamellibranchs; but alae are not tubular and, being adjacent to the hinge-line, their component valve-edges would scarcely have separated when the valves gaped apart.

spirolophous current-systems (Text-fig. 8 (*a*, *b*)), and those of the *Spirifer*-group must have had exhalant systems (Text-fig. 8 (*c–f*)). This follows naturally, since the inferred current-systems depend on the fundamental orientation of the filaments, which in turn depends on the sense of coiling of the spiralia, on which the two groups were defined. Just as the spiralia of the *Atrypa*-group cannot be transformed into those of the *Spirifer*-group except by being turned inside out, so also an inhalant spirolophe cannot be transformed into an exhalant except by the same operation.

On these reconstructions the actual form of the spiralia is clearly related to the efficiency of the feeding mechanism. The collecting capacity of the lophophore would have been dependent on the total area of the rows of filaments and hence on the total surface area of the cones formed by the spiral brachia. With either type of current-system the lophophore would, therefore, have had maximal efficiency if the spirals were closely moulded to the form of the mantle cavity, while leaving outside them a space adequate for the circulation of the water (cf. Text-fig. 7 (*c*, *d*)). This " moulding " is very conspicuous in the brachidia of many shells (Text-fig. 4, 8). It is interesting to note that in the *Spirifer*-group the posterior side of the brachidium was moulded to the " body " of the animal (the general position of which is indicated by the muscle scars) in two different ways: the proximal whorls are either deflected forwards or flared laterally (Text-fig. 4 (*c*, *d*)). The similar flaring on the anterior side of the brachidium must represent the point of emergence of the exhalant current from the interior of the spiralia. In shells with a median vertical deflection in the commissure (see Rudwick, 1959), this anterior flaring is related, in position and width, to the deflection, which thus appears to represent the median exhalant aperture. I hope to discuss elsewhere the functional significance of this relation between apertures and deflections.

IV. Conclusions

The inhalant and exhalant current-systems are in fact the only two ways in which any spirolophe can operate efficiently. This intrinsic limitation points to the probability that each type was evolved independently several times in the course of brachiopod evolution. Therefore, the occurrence of similarly oriented brachidia or lophophores and similar current-systems (observed or inferred) cannot, by itself, be taken as evidence for evolutionary affinity between different taxonomic groups.

The *inhalant* type of spirolophe occurs, unsupported by a brachidium, in craniaceans and rhynchonellids. It may also have occurred in various extinct groups, e.g. among orthoids. Supported by a brachidium, it is inferred that it occurred in atrypoids. The *exhalant* type is unknown in

living brachiopods, but may have occurred, unsupported by a brachidium, in extinct groups, e.g. it has often been suggested on the basis of shell-form that pentameraceans and such orthoids as *Platystrophia* may have had spirolophes like that of *Spirifer*. Supported by a brachidium, it is inferred that the exhalant type was characteristic of spiriferoids, and occurred also in the strophomenoid *Thecospira*. Assuming for the sake of argument that all these inferences are correct, spirolophes thus fall into four categories : the inhalant type with and without brachidium and the exhalant type with and without brachidium. The possible evolutionary relations between these categories are of considerable interest.

The multiple origin of the inhalant type would be suggested strongly, even without reference to fossil groups, by its occurrence in *Crania* and in *Tegulorhynchia*. The brachidial lamella of *Atrypa* was apparently the functional equivalent (as a supporting structure for the brachial axis) of the great brachial canal of rhynchonelloids. It therefore seems probable that atrypoids adopted the inhalant current-system independently of the rhynchonelloids or orthoids, utilizing an alternative mode of support. However, it is possible that atrypoids might have evolved from—or into—e.g. a rhynchonelloid or orthoid stock, by a change in the mode of support: this would have involved no alteration in feeding mechanism, but a taxonomically profound alteration in " hard-part " structure.

The relation between the brachidial and non-brachidial varieties of the exhalant type of spirolophe involves similar possibilities. The spiriferoids may have adopted the exhalant current-system independently of any non-brachidial stocks that utilized it; but alternatively they may have evolved from—or into—such stocks by changing the mode of support of the lophophore. Indeed this may have occurred several times, through the repeated appearance of brachidial lamellae, or at least the repeated development of crura into spiralia. Thus for example the non-strophic athyraceans (see Rudwick, 1959) may be totally unrelated to the strophic spiriferaceans; and similarly Williams (1953) has suggested that *Thecospira*, although a spire-bearing genus, is in fact related to the strophomenoids.

The extinction of all groups with the exhalant type of spirolophe cannot be attributed to their lesser efficiency. The inhalant type has no apparent functional superiority and the two varieties seem to be equally efficient alternative methods of disposing spirally coiled brachia within the restricted space of a mantle cavity. It is possible that transitions from one type to the other occurred during evolution. For example atrypoids may be directly related to spiriferoids. One could be derived from the other without the occurrence of any form with the plane spiralia theoretically necessary as an intermediate. For the

intermediate could have been represented by a form that became adult in the schizolophous stage, from which either type of spirolophe could have been derived subsequently by the operation of different growth-patterns in the lophophore. Thus the new stock could be cryptogenetic in the fossil record.

All these are intrinsic possibilities: their probability obviously depends on the detailed systematic and stratigraphical palaeontology of the groups concerned. Nevertheless, such possibilities emphasize the ambivalent character of "rates of evolution" and "rates of extinction" in brachiopods, when these are calculated merely on the stratigraphical ranges of taxonomic groups, the evolutionary integrity of which is highly uncertain. These possibilities also suggest the dangers of attempting to make evolutionary affinity the criterion of taxonomy in brachiopods, when characters of great practical value (e.g. the presence or absence of spiral brachidia) are likely to have arisen several times independently.

V. Acknowledgments

This work was begun during the tenure of the Harkness Scholarship at Cambridge, and continued with a Research Fellowship in Palaeontology at Trinity College, Cambridge. My unpublished work on living brachiopods, referred to briefly in this paper, has been made possible by a Royal Society and Nuffield Foundation Commonwealth Bursary and by a grant from the British Council. I would like to thank Dr. D. Atkins for her great generosity in giving me details of her unpublished work on living brachiopods. Mr. J. D. Campbell kindly read the manuscript of this paper and suggested improvements.

REFERENCES

Atkins, D., 1956. Ciliary feeding mechanisms of brachiopods. *Nature*, clxxvii, 706–7.

—— 1958. A new species and genus of Kraussinidae (Brachiopoda) with a note on feeding. *Proc. Zool. Soc. Lond.*, cxxxi, 559–581.

—— 1959*a*. The growth stages of the lophophore of the brachiopods *Platidia davidsoni* (Eudes Deslongchamps) and *P. anomoides* (Philippi), with notes on the feeding mechanism. *J. mar. biol. Ass. U.K.*, xxxviii, 103–132.

—— 1959*b*. The early growth stages and adult structure of the lophophore of *Macandrevia cranium* (Müller) (Brachiopoda, Dallinidae). *J. mar. biol. Ass. U.K.*, xxxviii, 335–350.

Bittner, A., 1890. Brachiopoden der Alpinen Trias. *Abh. der k.k. geol. Reichsanst.*, xiv, 1–325.

Chuang, S. H., 1956. The ciliary feeding mechanisms of *Lingula unguis* (L.) (Brachiopoda). *Proc. zool. Soc. Lond.*, cxxvii, 167–189.

Davidson, T., 1851–86. British fossil Brachiopoda. *Pal. Soc.*

Hancock, A., 1858. On the organization of the Brachiopoda. *Phil. Trans. Roy. Soc.*, cxlviii, 791–870.

Hyman, L. H., 1959. *The Invertebrates*; v., *Smaller coelomate groups*. New York.

MUIR-WOOD, H. M., 1955. *A history of the classification of the phylum Brachiopoda.* London.

ORTON, J. H., 1914. On ciliary mechanisms in brachiopods and some polychaetes, with a comparison of the ciliary mechanisms on the gills of molluscs, Protochordata, brachiopods, and cryptocephalous polychaetes, and an account of the endostyle of *Crepidula* and its allies. *J. mar. biol. Ass. U.K.*, x, 283–311.

PANTIN, C. F. A., 1951. Organic design. *The advancement of Science*, No. 30.

RICHARDS, J. R., 1952. The ciliary feeding mechanism of *Neothyris lenticularis* (Desh.). *J. Morph.*, xc, 65–91.

RUDWICK, M. J. S., 1959. The growth and form of brachiopod shells. *Geol. Mag.*, xcvi, 1–24.

THOMSON, J. A., 1927. Brachiopod morphology and genera (Recent and Tertiary). *New Zealand Board Sci. and Art, Manual* No. 7.

WILLIAMS, A., 1953. The classification of the strophomenoid brachiopods. *J. Wash. Acad. Sci.*, xliii, 1–13.

—— 1956. The calcareous shell of the Brachiopoda and its importance to their classification. *Biol. Rev.*, xxxi, 243–287.

SEDGWICK MUSEUM,
CAMBRIDGE.

An Occurrence of Tilleyite-Bearing Limestones in the Isle of Rhum, Inner Hebrides

By Charles J. Hughes

Abstract

Metamorphosed limestones carrying tilleyite are described from the northern slopes of Glen Dibidil, Isle of Rhum.

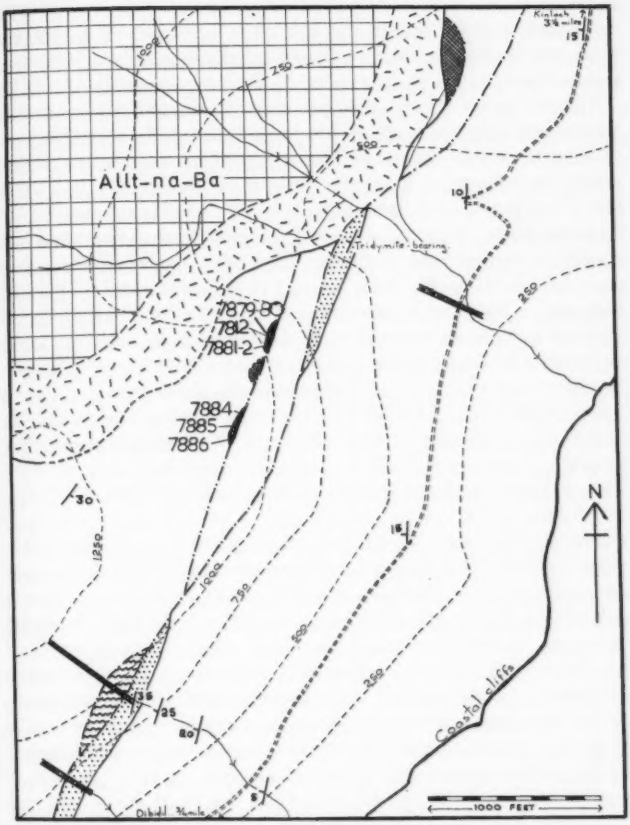
Geikie (1897, p. 351) records that on the northern slopes of Glen Dibidil in Rhum, he found a much altered grey and white limestone or marble. Harker, in his " Geology of the Small Isles of Inverness-shire " (1908), does not refer to this occurrence nor to any limestone in Rhum. During recent fieldwork on the island, concerned mainly with the southern mountains igneous complex, the writer found limestones in the valley of Allt-na-Ba, situated about a mile north of Dibidil; a subsequent search failed to reveal more of these rocks and it seems probable that they are the ones referred to by Geikie.

The limestones are not well exposed and their contact with the surrounding rocks, the Diabaig shales, is not seen. Preferential growth of grass and the position of small swallow-holes serve to delimit the extent of the limestones, which occur in two lenticular-shaped masses, each about fifty yards long and a few yards in width, along a line of dislocation parallel and close to the major Tertiary ring fault, an account of which has been given by Bailey (1945) (see Text-fig. 1). A small outcrop of granophyric rock, possibly intrusive, but very similar in appearance to metasomatized arenaceous Torridonian sediments investigated by the author (1955), is found between the two limestone masses in the same line of dislocation. A Tertiary gabbro, marginal to the large layered ultrabasic intrusion (Brown, 1956) of the island, outcrops nearby ; although not in contact with the limestone, its probable structure suggests that it underlies the northernmost limestone at no great depth.

The southernmost limestone is a homogeneous dull grey marble, of about 1 mm. grain size, which effervesces vigorously with cold dilute hydrochloric acid. Thin sections of three samples, 7884 to 7886,* show it to be a pure carbonate rock exhibiting a slight development of mortar structure.

In contrast to this, the northern limestone is variable in appearance and could accurately be described, following Geikie, as a much altered grey and white limestone or marble. The most striking rock type, occurring in one small outcrop, is a pale crystalline marble with a grain size of about 5 mm. ; other rocks have a dark grey and white mottled

* These numbers refer to the accession series of rocks in the Department of Geology and Mineralogy, Oxford, under the care of Professor L. R. Wager.


Allt-na-Ba
Tridymite-bearing
7879-80
7882
7881-2
7884
7885
7886
N
Coastal cliffs
1000 FEET
Applecross grits.
Diabaig shales.
Lewisian gneiss.
Limestone ?Lewisian.
Dolerite dyke.
Granophyre.
Ultrabasic rocks.
Marginal gabbro.

TEXT-FIG. 1.

appearance, due to the partial replacement of calcite by calc-silicate minerals.

Specimens of this impure grey and white limestone, 7812, 7879, and 7880, contain calcite, minor amounts of grossularite, diopside, vesuvianite, and leucoxene, and widely varying proportions of tilleyite.

Tilleyite comprises about 90 per cent of one thin section of 7812, whereas an adjoining rock, 7812B, is a coarse marble containing over 95 per cent calcite. The tilleyite, occurring in irregular multiple-twinned crystals, has the following optical properties : $\alpha = 1{\cdot}605$, $\beta = 1{\cdot}626$, $\gamma = 1{\cdot}651$; $\gamma{-}\alpha = 0{\cdot}046$; $2V\gamma = +88°$ (measured) and $+86°$ (calculated from indices) ; $X\Lambda a = 26°$ (determined on twin units by a maximum symmetrical extinction method) ; there are two good cleavages visible in the plane normal to β, one parallel to the twin composition plane, the other making an angle of 53° with it. The optical properties resemble those of tilleyite occurring in thermally metamorphosed limestone described by Nockolds (1947) from Carlingford, Northern Ireland, where a similar sporadic development of tilleyite has occurred. The habit of the Rhum tilleyite closely resembles that of the tilleyite figured in plate XI, fig. 2 of Nockolds' paper. The refractive indices of the Rhum tilleyite are very close to those of the tilleyite synthesized by Harker (1959) which had $\alpha = 1{\cdot}604$, $\beta = 1{\cdot}630$, $\gamma = 1{\cdot}653$.

In one place, similar altered limestone is cut by a syenite vein (7881), about 2 cm. in width, composed of microperthite and pale green augite rimmed by aegirine. Between this rock and altered limestone there is generally a very fine grained selvedge, about 1 mm. in width, consisting of augite, intermediate plagioclase and relatively large grains of pleochroic sphene. The mineral assemblage in the immediately adjacent limestone consists of wollastonite, grossularite, vesuvianite, calcite, leucoxene, and pyrite in this order of abundance. At the contact of altered limestone with the fine grained selvedge of the syenite veinlet, wollastonite forms prismatic crystals ; further away, it is poikiloblastic in habit and includes small grains of grossularite and vesuvianite ; wollastonite is not present in the altered limestone further away than 1 cm. from the contact with syenite.

It would appear that the northern limestone has undergone some degree of decarbonation and the metasomatic addition of Si plus minor amounts of Al, F, Ti, Fe, and S. This chemical change parallels that recorded by Tilley (1951) at the contact of the Beinn an Dubhaich granite with Durness limestone in Skye. The wollastonite recrystallization of limestone adjacent to the syenite vein is clearly related to it ; it is not quite certain, however, whether the apparently more widespread tilleyite-bearing rocks are related to this and possibly further unexposed similar veins or to a more generalized thermal metamorphism

surrounding the marginal gabbro. Further collecting, possibly from artificial exposures, would be desirable. It is noteworthy that the tilleyite occurs with calcite and small amounts of grossularite and vesuvianite indicating the presence of Al and F ; Harker (1959) notes the ready synthesis of tilleyite in the presence of these two elements. No spurrite was found.

The syenite vein in its mineralogy resembles syenite occurring in a similar relationship to altered limestone at Barnavave (Nockolds, 1937), and in a general way is analagous to an alkali facies of granite developed at granite contacts with dolomite in Skye (Tilley, 1949). It is possible that the syenite veinlet represents a desilicated facies of the nearby small granophyre mass, this being the only acid igneous rock exposed in the vicinity.

The age of these limestones is problematical. They lie in a fault zone, parallel and close to the major ring fault, with Torridonian Diabaig sediments on either side. No limestones other than occasional calcareous grits are recorded from Torridonian rocks in the North-West Highlands Memoir (Peach *et al.*, 1907), no calcareous varieties at all in the Small Isles Memoir (Harker, 1908), and none has been seen by the author in Rhum. It seems clear, therefore, that the limestones, which exhibit the effects of crushing, are faulted wedges emplaced in their present position by faulting related to the Rhum ring fault. There is evidence that during the history of this ring fault, although the aggregate displacement is everywhere upwards interiorly, movement in both senses has occurred, so that it would not have been impossible for a limestone mass from a higher or lower horizon to have been dragged along the fault out of its stratigraphical position. It is noteworthy that the unaltered limestone consists of calcite only and that none of the metasomatic or metamorphic minerals developed in the limestone contains significant amounts of magnesium. Durness limestone, in part of similar appearance, is present in Skye and comprises magnesian, non-magnesian, and siliceous varieties. Although the Lewisian limestones of the islands of Coll and Tiree are magnesian, pure calcite limestones have been recorded from Lewisian paragneisses (Peach, *et al.*, 1907, p. 81). A possible pointer to the stratigraphical position of the limestone is the presence, about 500 yards to the south along the ring fault, of a fault wedge of crushed Lewisian gneiss in a similar structural position between Torridonian sediments on either side, and it is tentatively suggested that the limestones in Rhum are of Lewisian age.

Acknowledgments.—The writer would like to record his appreciation of the facilities and help afforded him by Professor L. R. Wager and of profitable discussions with Dr. R. St. J. Lambert and other members of the Department of Geology and Mineralogy, Oxford.

REFERENCES

BAILEY, E. B., 1945. Tertiary igneous tectonics of Rhum, Inner Hebrides. *Quart. Journ. Geol. Soc.*, **100**, 165–191.

BROWN, G. M., 1956. Layered ultrabasic rocks of Rhum, Inner Hebrides. *Phil. Trans. Roy. Soc.*, ser. B, **240**, 1–53.

GEIKIE, A., 1897. *The ancient volcanoes of Great Britain*. Vol. 2. London.

HARKER, A., 1908. The geology of the Small Isles of Inverness-shire. *Mem. Geol. Surv. Scotland.*

HARKER, R. I., 1959. The synthesis and stability of Tilleyite $Ca_5Si_2O_7(CO_3)_2$. *Amer. Journ. Sci.*, **259**, 656–667.

HUGHES, C. J., 1955. Petrographical and structural studies in south-east Rhum, Inverness-shire. *D. Phil. thesis, Oxford.*

NOCKOLDS, S. R., 1937. Contributions to the geology of Barnavave, Carlingford, I.F.S. 2. An occurrence of quartz-bearing syenite and its xenoliths. *Geol. Mag.*, **74**, 125–132.

—— 1947. On tilleyite and its associated minerals from Carlingford, Ireland. *Miner. Mag.*, **28**, 151–158.

PEACH, B. N., *et al.*, 1907. The geological structure of the North-west Highlands of Scotland. *Mem. Geol. Surv. Great Britain.*

TILLEY, C. E., 1949. An alkali facies of granite at granite-dolomite contacts in Skye. *Geol. Mag.*, **86**, 81–93.

—— 1951. The zoned contact skarns of the Broadford area, Skye : a study of boron-fluorine metasomatism in dolomites. *Miner. Mag.*, **29**, 621–666.

GEOLOGICAL SURVEY
SALTPOND,
GHANA.

Cyclic Sedimentation: A Review

By Alan J. Wells *

Abstract

The well-known Carboniferous cyclothems of North America and Europe are discussed as examples to illustrate the great extent and lateral variation of sedimentary cycles. Very many other instances of cyclic sedimentation, in rocks of most ages, in many parts of the world, are also characterized by a more or less regular lateral migration of simultaneously existing depositional environments, caused by repeated transgressions and regressions of the sea over an epicontinental platform. Theories of varying complexity which have sought to explain cyclic sedimentation are briefly summarized, and it is suggested that the two basic requirements are a slowly subsiding sedimentary basin and more or less regular eustatic changes of sea level. The former will decide the geographical location. The latter could be a natural, periodic and world-wide consequence of the combination of the continuous effects of sedimentation and sostatic or orogenic movements of the sea floor.

Introduction

Sedimentary cycles of widely differing orders of magnitude have long been known from many parts of the geological column, but interest has been largely centred on the often very well-developed examples of Carboniferous age, both in Europe and in North America. This is not surprising, in view of the economic importance of the rocks involved. But it has resulted in disproportionately detailed knowledge of the Carboniferous cycles being readily available, and for many years the explanations which were put forward to account for cyclic sedimentation in general were based on consideration of specific and limited Carboniferous examples. It is the object of this paper to draw attention to the important lateral as well as vertical lithological variations within different types of cycle, and to emphasize their very widespread nature, both in time and space. It is believed that the Upper Palaeozoic cycles owe their marked development not to any abnormal geological process of the time, but to an unusual palaeogeography, when very wide continental platforms were invaded by shallow epicontinental seas.

This discussion is concerned with the large and diverse groups of cycles which have their origin in repeated transgressions and regressions of the sea over an epicontinental platform, with a resultant lateral movement of two or more adjacent and simultaneously existing environments of deposition in each of which a characteristic lithological

* Koninklijke/Shell Exploratie en Produktie Laboratorium (Shell Internationale Research Maatschappij N.V.)

type is developed. The deposits of such cycles have been described as being rhythmic by some authors and cyclic by others. Attempts have been made to attach distinct meanings to the two terms, but in fact there is often little difference in the sense in which they have been applied in the past. The essential concept of cyclic sedimentation, the deposits of which imply the repetition of a series of events rather than their mere recurrence, has remained the same.

Sedimentary Cycles in the Pennsylvanian of the United States

The first detailed study was made by Weller (1930), who gave the now familiar name of cyclothem to the deposits of a single cycle of deposition. He was primarily concerned with the cyclic succession in Illinois, but subsequent work has shown more or less similar cycles to occur in at least twelve states. Weller described an ideal cyclothem (a theoretically expectable composite succession, several phases of which are usually missing in any one locality), divided into a lower non-marine and an upper marine hemi-cyclothem. The lower part begins with a fine-grained sandstone (sometimes filling channels cut into the previous cyclothem), passes up through a sandy shale and an often discontinuous fresh-water limestone into an underclay and a coal. The marine part starts with a carbonaceous shale, sometimes containing a black limestone, passes up into a thick and continuous limestone, and finishes with a thick shale which becomes sandy towards the top. It was found that cyclothems could often be distinguished in isolated outcrops by lithological peculiarities, but that the further the correlation was carried, the less typical the Illinois cyclothem became because of fundamental lithological changes.

In the north Appalachian basin, the cyclothems as units are still very persistent, but the whole of the marine upper part can be replaced by non-marine shale. Cross and Arkle (1952) have found it impossible to give a single type of cyclic sequence for the Appalachian area because there are several facies of each cyclothemic unit as well as for each phase. It is apparent that successive cyclothems in an area of similar facies are more similar to one another than to their lateral equivalents in areas of different facies.

The cyclic succession in Kansas (Moore, 1936), although rather more complex than its equivalent in Illinois, shows remarkable lateral continuity. The marine members of cycles are particularly constant, and many individual cyclothems have been traced for over 400 miles along the outcrop and for over 300 miles down-dip, lateral continuity of correlation extending much farther to the east. In addition, groups of cycles have been distinguished in which each cyclothem is marked by some distinctive character. These megacyclothems exhibit regularity

of occurrence, and the microfaunas indicate repetition of environments at the same level in different megacyclothems, although some cycles or parts of cycles may be missing from megacyclothems in different places. Moore (1950) has noticed that the cyclothems in the middle of megacyclothems tend to have less well-developed marine phases than their companions, so that the megacyclothems appear as records of major fluctuations of the shore-line on which minor advances and retreats were superimposed.

In the south-western United States, the Pennsylvanian contains rather regular alternations of limestone and calcareous shale (Wanless and Patterson, 1952). The limestones are highly variable in lithology and include many of the common neritic and littoral lithological types. It is considered that the sequence was formed partly above and partly below wave-base, in an area which was remote from diastrophic activity, and that the regular alternations in this entirely marine succession are of the same origin as the contemporaneous well-developed cycles farther to the north-east.

It is thus possible to trace the progress of Pennsylvanian cyclic sedimentation across the American continent, from fully continental in parts of the Appalachians to fully marine in the south-west (Arizona and New Mexico). The typical Illinois cycle is the most complete type because it occurs in the central part, where shore-line movements were most marked, but it is not typical elsewhere. Lateral facies variations of the individual phases produce contemporaneous sequences with little or nothing in common between two areas except the cyclic nature. There is also great variation in the thickness of Pennsylvanian sediments in different areas, due to differences in the rate of subsidence during sedimentation. But it is important to note that the thick sequences are not more largely marine and do not include coarser clastic material than the thinner ones (Wanless, 1950). Cyclic deposition under such varying conditions implies widespread operation of some fundamental cause.

The essential flatness of the mid-continent during Pennsylvanian times is emphasized by the great lateral extent of individual coal seams. A single bed has proved to be workable over an area of 8,000 square miles in southern Illinois, and was probably formed over a much larger area than this. Under such conditions, with a very wide paludal environment extending inland from the coast, even a slight relative rise in sea level could be expected to inundate vast areas and shift the shore line by perhaps hundreds of miles. The thin marine bands resulting from these rapid transgressions are among the most characteristic features of such cycles, and they are found to be more reliable for correlation purposes than any particular lithological unit or succession.

SEDIMENTARY CYCLES IN THE CARBONIFEROUS OF EUROPE

Although the rhythmic nature of the Carboniferous sediments in parts of north-western Europe was certainly appreciated by miners during the eighteenth century, it was not until 1924 that the first detailed account of sedimentary cycles in the upper Viséan–lower Namurian Yoredale Series of northern England was given by Hudson. The general sequence of sandstone on shale on limestone is the same as that in many of the Pennsylvanian cyclothems of the United States, and the similarities are much more striking than the differences. There is sometimes a minor unconformity at the base of the main sandstone phase, but it is far more common to find a continuous passage. The break at the base of the transgressive limestone is normally taken as the beginning of the cycle, and this may appear to be a point of discrepancy with the North American cyclothems, Weller having originally defined the cycle as beginning at the time of maximum emergence. But it is now conceded that the phase chosen to begin the cycle may be regulated by convenience, provided that it is adequately defined and the term cyclothem is in general use for this type of sedimentary cycle wherever it is found.

Each complete Yoredale cyclothem is remarkably uniform in thickness (Dunham, 1950) and each transgression, coming from the south over a more or less plane surface, must have covered at least 2,000 square miles. Johnson (1958, 9) has shown how a thick open-water marine limestone, when traced northwards, splits up into a number of cyclothems, with first shales and then also sandstones and thin coals intercalated between the limestones. Still farther north, in Northumberland, the limestones members deteriorate into thin argillaceous marine bands in a dominantly deltaic succession. Deposition was in shallow water throughout and Stigmaria may be found *in situ* at the top of the sandstones. The evidence points to rapid deposition of the shale and sandstone members, with the coals and limestones representing relatively long periods of time.

During the Upper Carboniferous, cyclic sedimentation spread rapidly to cover much of northern Europe, which must have been dominated by the paludal environment. The Coal Measures are now known in such detail that a simple cyclic interpretation, valid in more marine successions, evidently represents an over-simplification of the evidence in many areas. In spite of variation in detail, however, the repetition of an essentially cyclic sequence is the outstanding characteristic in most coalfields.

In coal-measure sequences as a whole, the coal bed overlying a seat-earth is the only horizon which can give a reliable indication of base-level. It occurs normally at the boundary between marine and terrestrial deposition and is thus a key bed in any cyclothem. One of

the controlling factors in this type of cyclic sedimentation is evidently the quantity of detritus available. If it is high enough to keep the slowly subsiding basin continuously filled, nothing else gets a chance to appear in the sequence in that area. If it is too low, marine sedimentation may occur. But in any case, lateral movements of terrestrial depositional environments in sympathy with base-level movements were sufficiently well-marked for the same cycles to be detectable even in almost entirely non-marine sequences.

The Coal Measures of Belgium and the Netherlands, in particular, show a well-marked development in time. Marine horizons are numerous in the Namurian and the coal horizons are very poorly developed (Pannekoek, *et al.*, 1956). The middle part of the Namurian contains cyclothems up to nearly 250 feet in thickness, a marine fauna occurring in the shales (often bituminous in their lower part) which overly the potential coal beds (van Leckwijck, 1952). In the lower part of the Westphalian, however, regular workable coals occur and fresh-water deposits become more important. Terrigenous material increases and the cyclothems above the marine band separating Westphalian B and C (traceable all over western Europe) are completely non-marine. For the most part, they contain only thin coal stringers, but in the Pas de Calais the continental Westphalian C is greatly expanded (over 3,000 feet thick), and contains many regularly-spaced and well-developed seams (Bouroz, 1959). The vertical facies development in the north-west European coal province can thus be compared with the lateral variation of Pennsylvanian cyclothems between Illinois and the north Appalachian Basin.

The cyclic succession in Belgium can be followed in detail into the Aachen coalfield (Fiege, Lambrecht, and van Leckwijck, 1957) and over 300 cyclothems have been detected in the Namurian and Westphalian of the Ruhr (Jessen, 1956). In eastern Europe, the Upper Carboniferous of the Donetz basin also contains well-marked coal-bearing cyclothems (Trueman, 1946), comparable to those in parts of the American mid-continent. It is evident, therefore, that the large area over which Upper Carboniferous cyclic sedimentation took place in Europe is at least comparable in size with the area of Pennsylvanian cyclic deposits in the United States. The European deposits have been somewhat more isolated by folding and erosion, increasing the difficulties of inter-basin comparisons. But the principal difference seems to be that in a general way, the European Upper Carboniferous has been exposed mainly at right angles to the direction of the shoreline movements of the period, while in America the converse is true. This has resulted in rather greater continuity of lithological types in Europe, although it is much less easy to appreciate the lateral developments of cyclothems between marine and continental environments.

Coal-bearing sedimentary cycles are present in the lower Gondwana (Upper Carboniferous–Permian) of Peninsular India, where largely terrestrial cyclothems are repeated with only minor variations in different basins (Jacob, 1952). Thick coal-bearing Upper Carboniferous cyclic successions are also known from places as widely separated as China and Antarctica and it is, therefore, no exaggeration to describe the mechanisms involved in cyclic sedimentation as being of world-wide occurrence, at least during the Upper Carboniferous. But there are now very numerous accounts of well-marked sedimentary cycles of other ages, scattered throughout the geological column and many more certainly remain to be described. For the present purpose, a few representative examples will serve to illustrate their variety and distribution.

Other Examples of Sedimentary Cycles

(*a*) Well-developed cyclic deposits have been described by Young (1957) from the upper Cretaceous of eastern Utah. In each cycle, four sedimentary facies are recognized, corresponding with off-shore marine, littoral marine, lagoonal–paludal, and terrestrial environments. In response to relative sea level changes, these environments moved first landwards and then seawards, resulting in an intricate interfingering of the different facies. Each cyclothem is assumed to begin with a rapid transgression and deposition of marine shale. A sand bar or beach forming at or near the line of maximum transgression graded seaward into silt and mud, and as the beach grew seawards, it rested on mud. Where seaward growth continued long enough a broad apron of sand resulted. Lagoons, flanked by small coal swamps, formed behind the bar and as these became filled with sediment, extensive coal swamps spread over the lagoonal area. If the subsequent transgression was only a minor one, a new sand bar formed on top of the previous one and the coal swamp was not destroyed. On the contrary, a series of minor transgressions produced unusually thick coals. Occasionally a much greater transgression moved the shore-line far inland and the whole process started again. Even so, the coastal plain was evidently much narrower and the relative changes in sea level more modest than in Pennsylvanian times. But these deposits clearly and simply display, on a reduced scale, many of the essential features of oscillating environments found in the extensive Upper Carboniferous cyclothems. They can be closely matched by sediments from some recent coastal plain environments.

(*b*) Four well-marked Eocene sedimentary cycles in the central Gulf Coast area, each due to a major invasion of the sea into the Mississippi embayment, have been described by Bornhauser (1947). Each cycle consists very broadly of a basal marl, calcareous shale, and

glauconitic sand, grading up through dark shale into sandstone, shale, and lignite. As is commonly observed elsewhere, the rapid transgressive phases are poorly represented in the succession. But the regressive phases left impressive and considerably varied sequences, each major cycle having superimposed minor cycles which reflect shore-line oscillations during regression.

(*c*) The Eocene of north-west Europe also displays large-scale cycles of sedimentation (Stamp, 1921). A single basin, probably open to the north-east, extended over most of southern England, northern France, and Belgium, and periodic transgressions and regressions of the sea took place throughout the Eocene. Each of the six resulting cycles, of regularly alternating marine and continental beds, consist principally of clay, but started and finished with coarse clastic sediment.

(*d*) Cyclic sedimentation has long been known in the Jurassic of north-west Europe (Arkell, 1933). The deposition of limestone on sandstone on clay occurred at least nine times in England, although there is considerable lateral variation and the three facies did not spread over anything like the whole area. In the Lower Jurassic (Lias) of Alsace, a predominantly argillaceous sequence is broken by many thin limestone bands which grade up from the clay through marl, with a sudden return to clay again above the limestone. A common variant of the limestone is a shell bank and either of these marks a faunal as well as a lithological break, representing not only a shallowing of the sea, but also a distinct time gap.

(*e*) A more restricted example of Jurassic cyclic sedimentation is described from the Lias of Yorkshire by Hemingway (1951). Three cycles of limited extent begin with black bituminous shales, which become progressively less black and contain calcareous concretions in their upper part. They grade upwards through fine argillaceous sandstones into ironstone, so that a progressive upward increase in oxidation is apparent. Hemingway compares such a succession with progressively shallower deposits of the modern Black Sea.

(*f*) The Williston basin of Saskatchewan contains Devonian and Mississippian cyclic deposits of considerable thickness. The Middle and Upper Devonian succession contains many cycles which show a development from a basal shale through bedded limestone to reef limestones and evaporites, although this may sometimes be obscured by local tectonics (Baillie, 1955). The withdrawal of the Mississippian sea from the north-east rim of the basin was an interplay of retreat and re-advance, and seven cyclic units in the upper Madison Limestone show a progressively weakening marine transgression at each stage, with continental conditions advancing further into the basin with each retreat (Fuller, 1956). Each cyclothem, beginning with a re-advance, consists of a basal shale passing upwards into oolitic and

algal limestones. During retreat, the limestone became muddy, and the cycle finished with evaporites, usually in the form of anhydrite.

(*g*) The Triassic Moenkopi formation of Arizona and Utah is marine in the west and continental in the east. Inter-fingering of the major environments by wide movements of the shore-line was due to oscillations of relative sea-level and McKee (1954) has recognized at least seven cyclothems. These consist essentially of shallow-water marine limestone and calcareous siltstone overlain by continental mudstones, sandstones, and lagoon deposits which locally yield bones of reptiles.

(*h*) Calcareous cycles have been described by Brückner (1953) from the Helvetic Series in the Swiss Alps. A well-developed cycle starts with shaly or marly beds at the base and passes through alternating marl and limestone into continuous limestone. The transition to the next cycle may be either sharp or through marl alternations, and the main feature throughout is an alternate increase and decrease in the proportion of carbonate.

(*i*) Sub-surface sections in non-glacial Pleistocene deposits in the Po and Ganges deltas show successions said to be similar to cyclothems from the Pennsylvanian (Wanless, 1950). Similar cycles are also known from other deltas, and from the coastal plain area of Texas. Holocene deposits in the Mississippi delta show a clear succession of transgressive marine deposits and pro-deltaic silts and clays beneath variable regressive sediments (U.S. Army Engineers, 1958), the similarities between this sequence and many cyclothems of coal-bearing type being indeed striking.

The best-developed cycles are thus often those which include coal in the sequence and it appears that the paludal and paralic environments are important and often critical ones in the development of cyclothems, although there are all stages from fully marine to fully continental cycles. This intermediate type, with maximum alternation of environment, was probably often associated more with a wide coastal inter-deltaic plain, where deltaic deposits could be partly redistributed by long-shore currents, rather than with geographically restricted and much more variable truly deltaic conditions such as have been put forward by D. Moore (1958) to explain the Yoredale cyclothems of Upper Wensleydale in the north of England.

Another normal feature of cyclothems is the dominance of sediment deposited during the regressive phase, the deposits of the transgressive part of the cycle being generally very subordinate and sometimes even unrepresented. If the gradual subsidence of the basin of deposition (to accommodate sediment) and the relative oscillations in sea-level (of whatever cause) are regarded as being two separate but superimposed effects, the transgressive phase will naturally proceed more

rapidly than the regressive one and will get less of an opportunity to be represented in the sedimentary column if subsidence is uninterrupted.

Theories to Explain the Origin of Sedimentary Cycles

The earliest theories, which sought to explain the presence of coal rather than the origin of the cyclothems containing them, assumed that subsidence of the depositional basin was marked by pauses long enough for the silting up of lagoons and the spread of coal jungles (Geikie, 1882, and earlier). Rather more elaborate explanations have since been attempted and the more important of these can be briefly summarized as follows :—

(*a*) *Differential Uplift Theory* (Hudson, 1924).

The Yoredale cyclothems of Yorkshire were first explained by changes in the type and amount of sediment delivered to a gradually subsiding basin, each cycle being held to result from an uplift of the source area followed by denudation. The source of the sediments was considered for the first time, but it is unlikely that erosion would have proceeded to a mature stage during each of the many widespread cycles which require to be explained. Something more than just gradual subsidence seems to be required in the area of deposition.

(*b*) *Diastrophic Control Theory* (Weller, 1930–1956).

This elaborate theory, based on much detailed field observation of Pennsylvanian cycles in the United States, requires alternate pulsating uplift and depression of large continental areas, the magnitude being greatest in the uplands and declining basinwards. Although subsidence was dominant in the basin, emergence is held to have been not only the result of filling because the vertical movements necessary to account for the deposition of different types of sediment are thought by Weller to be some 5–10 times the thickness of individual cyclothems. It is also thought that although uplift was dominant in the source area, intermittent subsidence is indicated by the grain size of the basin sediments.

As cyclothems of comparable age are known in widely separated parts of the world, such a theory requires that large and distant areas should have been simultaneously pulsating, with a delicate balance which was repeated during each cycle. It was to obviate the necessity for this apparently ungeological process that another and totally different mechanism was put forward.

(*c*) *Glacial Control Theory* (Wanless and Shepard, 1936).

The evidence of considerable world-wide sea-level fluctuations during the Pleistocene due to alternate advance and retreat of the ice caps

suggested that Pennsylvanian cyclothems might be explained if each major transgression was due to melting of ice caps during an interglacial period of the Gondwana glaciation. Largely non-marine cycles could then be easily explained by climatic variations associated with glaciation, given intermittent subsidence in the depositional area. The theory fails, however, when the many cyclothems of other ages are considered, because in most cases there is no evidence whatever of contemporaneous continental glaciation. Wanless (1950) has used the non-glacial cyclic successions of Quaternary age in modern deltaic and interdeltaic areas as strong evidence in favour of the glacial control theory. He does not consider that they might be a continuation of similar cycles of Tertiary age in the same areas, as is the case in the Gulf Coast region.

The original theory of glacial control has been considerably elaborated by Wheeler and Murray (1957), who inferred relationships between the meteorological glacial theory of Simpson (1934) and Weller's Illinios cyclothem. Simpson explains two glacial and two interglacial periods (one long, cold, and arid; the other short, warm, and wet) by a single cycle of solar radiation and Wheeler and Murray have conveniently found that the typical Pennsylvanian cyclothem should be regarded as indicating not two but four base-level reversals. The extension of Simpson's hypothesis (adapted to the Pleistocene glaciation) to pre-Quaternary geological phenomena immediately places this modified theory in the realms of speculation, and the increased number of base-level changes is not only unnecessary to the environmental interpretation of normal cyclothems, but in many cases is plainly undesirable.

(*d*) *Compaction Control Theory* (van der Heide, 1950).

Van der Heide draws attention to the considerable local variation which must have been superimposed on the generally uniform development of extensive areas of deposition, to account for such phenomena as splitting of coal seams, where a whole succession may develop laterally from an insignificant parting. He recalls the suggestion made over forty years ago by Kendall, that compaction of peat layers might play an important part in the process and concludes, from studies of the Coal Measures in southern Limburg (Netherlands), that a generally uniform subsidence combined with compaction can sufficiently explain the sedimentary cycles.

A normal cycle is visualized as consisting of a silting-up phase, with deposition faster than subsidence, followed by emergence and growth of vegetation with peat formation slower than subsidence. This would lead to eventual drowning, when rapid compaction of the peat would accelerate the transgression and help to account for the sudden change

from paludal to open marine conditions. Dunham (1950), for the same reason, has suggested that subsidence was not uniform and that drowning could also have been caused by the additional factor of renewed general subsidence resulting from delayed isostatic adjustment to the rapidly accumulated load.

The change to marine conditions may not, however, have been as sudden as it appears. Rise of sea-level will, of course, normally have combined with subsidence to make transgression proceed much more rapidly than regression, during which the two effects will be opposed. But the deposits of the transgressive phase are also naturally poorly represented, because less and less sediment is carried out to sea as base-level rises and the rate of deposition falls very sharply. It may even fall to zero, sedimentation being by no means a necessary consequence of marine conditions.

There must undoubtedly have been considerable compaction of the type visualized by van der Heide in some cyclic successions and it is probable that there was also some variation in the rate of subsidence. But the fact that cyclothems have essentially the same nature, whether or not they have any connection with coal, suggests that compaction of peat cannot have been a significant factor in their genesis, although it may well have had important local effects.

(*e*) *Plant Control Theory* (Robertson, 1952).

Vegetation spreading into a lagoon as it silts up would be capable of trapping sediment with its roots and thus extending its sphere of influence. The theory considers that the formation of peat managed to keep pace with a subsiding swamp floor within quite wide limits and so to modify the ground on which it grew to suit its own convenience. This influence would continue until the area was submerged by the break-down of a beach-bar, when uneven compaction of different deposits would tend to minimize the recorded effect of plant control, although both factors would be causes of cyclic sedimentation. Robertson concludes that the coal-bearing cycle is not so much a sequence to which coal has been added, as one more or less modified by the influence of vegetation. This may well be so, but it has relatively little bearing on the formation of many cyclothems where coal is either absent or represented by a mere streak. The coal-bearing cycles occur in only a part of the much larger area of cyclic deposition, so that although plant control may have been of local importance, it can barely have had an overall genetic effect.

Conclusions

It is not thought that any of these theories, in its present form, can convincingly account for the origin of widespread cyclic sedimentation

at various times. But a reasonable interpretation of the evidence seems to point, in general, to the formation of sedimentary cycles by more or less regular eustatic changes of sea-level affecting a slowly subsiding basin of deposition, as suggested (among others) by van Leckwijck (1949). If this principle is admitted, it is possible to make an approach to the problem along the lines originally taken by Wanless and Shepard, but without having to invoke glaciation to account for all sea-level fluctuations.

The changes in relative sea-level which must have accompanied the deposition of cyclothems have been variously estimated, but all have been several times greater than the thicknesses of the cyclothems themselves. This has led to difficulties in accounting for the supposed magnitude and suddenness of such changes. But current sedimentological work suggests that these changes may have been very much smaller than was previously believed. Channels in various modern deltaic environments are now known to be often very largely cut and filled below sea-level, so that the presence of channeling is in itself no criterion of uplift. The depth of deposition of the marine phases, particularly the limestones, was also probably very shallow, and in many cases need not have exceeded a few tens of feet. Van Leckwijck has shown the writer one of a number of thin coal seams within a normal carbonate succession in the Upper Viséan of Belgium, the marine limestone underlying the coal having been clearly reworked by rootlets before lithification. There is other impressive evidence of shallowness from analogy with recent sediments and it is thought that the observed facts can often be explained by eustatic sea-level changes of as little as 50 feet, when combined with subsidence to accommodate the sediments. Evidence of constant movement of sea-level is present on virtually any modern coral island.

Eustatic changes can be caused by alteration of the total volume of water on the earth's surface, by growth and decay of glaciers and lakes, and by alteration in the shape of the sea basins by sedimentation and isostatic or orogenic movements of the sea floor. The effect of the first, principally from volcanic activity and absorption by minerals during weathering, has been calculated by Kuenen (1950), and is evidently too slow a factor to materially affect the present argument. Although the second is known to have produced sea-level changes of ample magnitude during the Pleistocene, an additional factor is required because of the lack of evidence of glaciation contemporaneous with many of the numerous occurrences of cyclothems which have to be explained. But the third factor is surely capable of sufficiently affecting world-wide sea-levels, although local relative movements, whether due to the same cause or not, would tend to obscure such eustatic changes unless they are considered from more general indications.

Enormous quantities of sediment are continuously being poured into the sea, for the most part associated with deltas of various types. It is hardly to be expected that the consequent total displacement of water will be even approximately balanced, at any one time, by corresponding contemporaneous downward movements of those or other parts of the sea bed. It seems logical to imagine the two processes of displacement of water by sedimentation and accommodation of water by sea bottom movements as proceeding side by side and of the same order of magnitude, but by no means always counteracting one another. This would result in a continual oscillation of absolute sea-level by perfectly normal geological processes. As it is the sum total of world-wide events that is involved and as overall tectonic activity is surely as continuous a process as sedimentation, it is suggested that the effect of the combination of movements of the sea-bed throughout the oceans and displacement by sedimentation produced fluctuations of sea-level, which may at times have become rather regular. In no case would it be necessary to invoke actual individual tectonic rhythms in any one place, and the only requirement for the development of cyclic sedimentation during such a period of regular sea-level changes would then be a gently subsiding basin of deposition.

If such a process of eustatic control could be established and the frequency, similarity, and wide distribution of cyclothems suggests a simple, fundamental, and recurring process, the implications for correlation are obvious, as it would mean that the major transgressions and regressions of the sea would have a world-wide cause. This conclusion is in no way a new idea and has often been suggested before. But it is held that comparison of the different types of cyclothem developed in rocks of many different ages strongly suggests a common cause. Local relative movements in any area will of course tend to complicate and often obliterate, the effects of any general changes of base-level, so that correlation will not often be so straightforward as might be supposed. For instance, if the rate of subsidence in a depositional basin should vary, or if the subsidence should be intermittent, the emphasis of the various transgressive and regressive environments in the sediments will also vary. This is a common enough feature in the lateral variation of cyclothems. So although the effects of the numerous transgressions recorded in cyclothemic deposits vary greatly from place to place, it is suggested that the transgressions themselves were due to world-wide causes and that if the effects of local and often large base-level changes can be eliminated, it should be possible to carry reliable correlations over very great distances.

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REFERENCES

ARKELL, W. J., 1933. *The Jurassic System in Britain.* Oxford.

BAILLIE, A. D., 1955. Devonian System of the Williston Basin Area. *Bull. Am. Asst. Pet. Geol.*, xxxix, 575–629.

BORNHAUSER, M., 1947. Marine sedimentary cycles of Tertiary in Mississippi embayment and Central Gulf Coast area. *Bull. Am. Ass. Pet. Geol.*, xxxi, 698–712.

BOUROZ, A., 1959. La formation des séries Houillères dans leur contexte paléogéographique. *C.R. réunion de Sédimentologie*, Arras, 13th–15th March.

BRÜCKNER, W. D., 1953. Cyclic calcareous sedimentation as an index of climatic variations in the past. *Journ. Sediment. Petrol.*, xxiii, 235–237.

CROSS, A. T., and ARKLE, T., 1952. The Stratigraphy, sedimentation and nomenclature of the upper Pennsylvanian-lower Permian (Dunkard) strata of the Appalachian area. *C.R. 3e Cong. Strat. et Géol. du Carbon.*, Heerlen, 101–111.

DUNHAM, K. C., 1950. Lower Carboniferous sedimentation in the northern Pennines (England). *Rept. 18th Int. Geol. Cong.*, Pt. 4, 46–63.

FIEGE, K., LAMBRECHT, L., and VAN LECKWIJCK, W., 1957. Zur Stratinomie des Oberkarbons des Aachener Gebietes und des belgischen Grenzlandes. *Neues Jb. Geol. u. Paläontol.*, Abh. 104, 299–358.

FULLER, J. G. C. M., 1956. Madison Limestone in S.E. Saskatchewan. *Oil in Canada*, August, 1956, 34–58.

GEIKIE, A., 1882. *Text-book of Geology*, London.

HEMINGWAY, J. E., 1951. Cyclic Sedimentation and the Deposition of Ironstone in the Yorkshire Lias. *Proc. Yorks. Geol. Soc.*, xxviii, 67–74.

HEIDE, S. VAN DER, 1950. Compaction as a possible factor in upper Carboniferous rhythmic sedimentation. *Rept. 18th Int. Geol. Cong.*, Pt. 4, 38–45.

HUDSON, R. G. S., 1924. On the rhythmic succession of the Yoredale Series in Wensleydale. *Proc. Yorks. Geol. Soc.*, xx, 125–135.

JACOB, K., 1952. A brief summary of the Stratigraphy and Palaeontology of the Gondwana System. *19e Cong. Géol. Int.*, (Symposium sur les Séries de Gondwana), 153–174.

JESSEN, W., 1956. Das Ruhrkarbon als Beispiel für extratellurisch verursachte Zyklizitäts-Erscheinungen. *Geol. Jb.*, lxxi, 1–20.

JOHNSON, G. A. L., 1958. Lateral variation of marine and deltaic sediments in cyclothemic deposits, with particular reference to the Visean and Namurian of northern England. *C.R. 4e Cong. Strat. et Géol. du Carbon,*, Heerlen (in press).

—— 1959. Palaeogeography of the northern Pennines and part of north-east England during the deposition of Carboniferous cyclothemic deposits. *Paper submitted to section 12, 21st Int. Geol. Cong.*, Copenhagen, 1960.

KUENEN, Ph.H., 1950. *Marine Geology*. New York.
LECKWIJCK, W. VAN, 1949. Sur la sedimentation dans le terrain houiller de la Campine belge à l'époque du Westphalien B inférieur (Zone d'Asch). *Ann. Soc. Géol. de Belg.*, lxxii, B439–468.
—— 1952. Étude géologique du gisement houiller d'Andenne-Huy. Le Namurien dans le basin d'Andenne. *Publ. Ass. Étude Paléont. et Strat. houillères*, II, (Brussels, 1952).
MCKEE, E. D., 1954. Relationship between Fauna and Lithology in the Moenkopi Formation. *Journ. Sediment. Petrol.*, xxiv, 136.
MOORE, D., 1958. The Yoredale Series of upper Wensleydale and adjacent parts of north-west Yorkshire. *Proc. Yorks. Geol. Soc.*, xxxi, 91–136.
MOORE, R. C., 1936. Stratigraphic classification of the Pennsylvanian rocks of Kansas. *Geol. Surv. Kansas*, Bull. 22.
—— 1950. Late Palaeozoic cyclic sedimentation in central United States. *Rept. 18th Int. Geol. Cong.*, Pt. 4, 5–16.
PANNEKOEK, A. J., *et al.*, 1956. *Geological History of the Netherlands*. Staatsdrukkerij en Uitgeverijbedrijf, 's-Gravenhage.
ROBERTSON, T., 1952. Plant Control in rhythmic sedimentation. *C.R. 3e Cong. Strat. et Géol. du Carbon.*, Heerlen, 515–521.
SIMPSON, G. C., 1934. World climate during the Quaternary Period. *Quart. Journ. Roy. Met. Soc.*, lx, 425–478.
STAMP, L. D., 1921. On cycles of sedimentation in the Eocene strata of the Anglo-Franco-Belgian Basin. *Geol. Mag.*, lxiii, 108–114, 146–157, 194–200.
TRUEMAN, A. E., 1946. Stratigraphical problems in the Coal Measures of Europe and North America. *Quart. Journ. Geol. Soc.*, cii, 49–93.
U.S. ARMY ENGINEERS, 1958. Geology of the Mississippi River Deltaic plain. *Tech. Rept. No. 3-483, Waterways Experiment. Station*, Vicksbury, Miss.
WANLESS, H. R., 1950. Late Palaeozoic cycles of sedimentation in the United States. *Rept. 18th Int. Geol. Cong.*, Pt. 4, 17–28.
—— and SHEPARD, F. P., 1936. Sea level and climatic changes related to late Palaeozoic cycles. *Bull. Geol. Soc. Amer.*, xlvii, 1177–1206.
—— and PATTERSON, J., 1952. Cyclic sedimentation in the marine Pennsylvanian of the south-western U.S. *C.R. 3e Cong. Strat. et Géol. du Carbon.*, Heerlen, 655–664.
WELLER, J. M., 1930. Cyclical sedimentation of the Pennsylvanian period and its significance. *Journ. Geol.*, xxxviii, 97–135.
—— 1956. Argument for Diastrophic Control of late Palaeozoic cyclothems. *Bull. Am. Ass. Pet. Geol.*, xl, 17–50.
WHEELER, H. E., and MURRAY, H. H., 1957. Base level control patterns in cyclothemic sedimentation. *Ibid.*, xli, 1985–2011.
YOUNG, R. G., 1957. Late Cretaceous cyclic deposits, Book Cliffs, eastern Utah. *Ibid.*, xli, 1760–1774.

BROEKMOLENWEG 20,
DELFT, NETHERLANDS.

Large Scale Patterned Ground in the Valley of the Worcestershire Avon

By F. W. Shotton

(PLATE XI)

Abstract

Crop markings reveal a polygonal network resembling that of "patterned ground" in arctic Alaska. From this the former presence of perennially frozen ground is inferred, with the implication that the mean annual isotherm of this part of Worcestershire was at least 13½° C. lower than it is at present. It is argued that this condition obtained at the period of the Irish Sea Glaciation maximum.

The oblique air photograph of Pl. XI, fig. 1, is part of one taken by Mr. W. A. Baker, of Malvern, to whom I am indebted for allowing its reproduction. The site is on the west side of the River Avon, ½ mile west of Abbot's Salford and four miles north-north-east of Evesham, map reference SP 060501, Latitude 52° 9′ N., Longitude 1° 55′ W. It was photographed in late July, 1958, and the differential ripening of the crops brings out a system of large polygonal markings which are clearly the result of some natural process modifying the permeability of the subsoil and not due to human agency. The polygons vary in size, the smallest being about 25 feet across, the largest perhaps 80 or 100 feet.

This is not the first occasion on which markings of this type have been revealed by crop photography, but it is a more detailed example than any others I know. Arkell (1947, p. 239), following Riley (1945), illustrated a pattern on the Three Pigeons plateau, 9 miles east of Oxford. In this case the individual polygons are few and large, some being certainly the enclosing outline of several smaller ones not completed. The smallest are about 130 feet across, the largest over 500 feet. Arkell indicated that these problematical crop marks were spread over several different Pleistocene deposits—"they are commonest on the Summertown Terrace, including the higher parts of it that grade up into the Wolvercote Terrace, and rare on the Northmoor Terrace, but the most striking and widest examples occur on the 150 foot terrace of the Three Pigeons plateau." He ascribed them to the disturbance produced in the gravels by a polygonal system of ice-wedges, as described by Leffingwell (1919).

The polygonal outlines of the Abbot's Salford picture immediately recall the "patterned ground" of the arctic tundra where perennially frozen ground underlies a thin active layer of soil subject to seasonal frost and thaw. I am indebted to Dr. Robert F. Black of the University of Wisconsin, for the photograph reproduced in Pl. XI, fig. 2, of

present-day patterned ground in northern Alaska, one of a series taken by the U.S. Coast and Geodetic Survey of 1947. He informs me that here the " permafrost " layer is 800 feet thick.

Frost (1952) distinguishes three different categories of these large polygons:—

(*a*) With depressed centres surrounded by raised walls which often carry a median channel. Number of sides typically between four and six.

(*b*) With raised centres and depressed perimeter channels, similar in shape to (*a*).

(*c*) Rectangular polygons, said to be confined to low lying gravel areas.

The diameter of these polygons ranges normally between a lower limit of 15 or 20 feet and an upper one of 200 feet. Within them, particularly in the case of (*b*), there may be a secondary system of much smaller polygons.

The Alaskan photograph (Pl. XI, fig. 2) shows mainly examples of type (*a*) on a low river terrace with (*c*) on the meander scrolls at the bottom right hand side. It is obvious that the crop markings resemble both (*a*) and (*b*), but there seems no way of deciding which type was originally present and the size range is consistent with either.

These large ice-wedge polygons are not to be confused with the small stone polygons, a few feet in diameter, which are so often seen in vertical sections of British Pleistocene deposits as " festoons " and patches of upturned pebbles. Although these small-scale effects are common in the active soil layer overlying perennially frozen ground, they are not confined to regions with permafrost, but occur in somewhat more genial climates provided that they experience an alternation of severe frost and thaw. On the other hand, Frost (1952) refers to large-scale patterned ground as " one of the chief identifying features of permanently frozen ground ". If then we can assume this equation of patterned ground with permafrost and that the crop markings show the former existence of ice-wedge polygons, it follows that at the time of their formation the Avon valley had a mean annual temperature a few degrees below freezing point. If we are to judge by Alaska where the 0° C. isotherm lies south of the limit of permafrost, the mean annual temperature would not be higher than 26° F. (c. $-3\frac{1}{2}$° C.), at least 24° F. ($13\frac{1}{2}$° C.) below that of present-day Worcestershire.

It is of interest to enquire how far it is possible to locate this particular episode of permafrost in time. The sequence of events after the Older Drift and No. 5 Terrace may be summarized as follows (Tomlinson, 1925, 1935, Shotton, 1953) with all height figures referring to the immediate locality of Abbot's Salford.

(i) Aggradation of gravels with warm fauna (*Hippopotamus, Elephas antiquus, Belgrandia marginata*). These underlie No. 3 Terrace.

(ii) Continued aggradation with warm-temperate fauna (main gravels of No. 4 Terrace).

(iii) Downcutting to a surface 64–75 feet above present alluvium. Cold climate with cryoturbation.

(iv) Aggradation of 4 or 5 feet of gravel. *Elephas primigenius*, late Acheulian and Levalloisian implements. Formation of No. 4 Terrace surface 68–79 feet above alluvium.

(v) Downcutting to No. 3 Terrace surface followed by a pause (c. 40 feet above alluvium, surface not preserved at this particular place).

(vi) Downcutting to about alluvium level.

(vii) Aggradation of gravels with cold fauna (*Elephas primigenius, Bison priscus, Rangifer tarandus, Tichorhinus antiquitatus*) to 25 feet above alluvium. No. 2 Terrace feature.

(viii) Downcutting to about 5 feet below alluvium.

(ix) Aggradation to 5 feet above alluvium (No. 1 Terrace feature).

(x) Downcutting to 15 feet below alluvium.

(xi) Aggradation to modern alluvial plain.

Stage (i) is correlated with the Eemian inter-glacial (Riss/Würm) and (vi) with the probable maximum intensity of the Würm glaciation in England.

In attempting to relate the production of this patterned ground to the sequence of events given above, it is clear that it happened not earlier than stage (iv), but it could date from a later period. In this connection it is important to realise (Text-fig. 1 A and B) that No. 4 Terrace is cut through by a stream, on the east side of which the gravels attain a height of 154 feet (i.e. 68 feet above alluvium) and the base of the gravels is close to 145 feet. On the other side of the stream the terrace is a little higher, until it attains 165 feet at its back. Between these two relics, the stream cuts down to about 122 feet in the area of the photograph, Pl. XI, fig. 1.

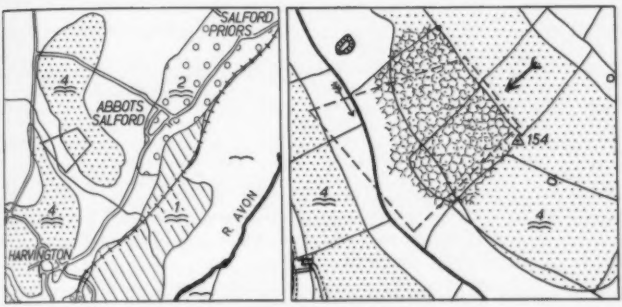
On Text-fig. 1 B is indicated the extent to which polygon structure can be seen on the original photograph taken by Mr. Baker (of which Pl. XI, fig. 1 is a part). It certainly occurs from the summit of the terrace, across its edge and on to the Keuper Marl as low as 130 feet O.D. Beyond this the distance and obliquity of the photograph prevent reliable interpretation, though there is a suggestion of a much smaller scale of pattern which, if present, must be a shallow surface feature. Disregarding this, the pattern can be explained on the alternative views:

(*a*) that it was produced on No. 4 Terrace surface and that it is now

seen nearly 30 feet below this, in the Keuper Marl, because erosion has since cut that depth into the polygonal columns;

(*b*) that it was produced long after the period of No. 4 Terrace on an eroded surface not very different from that which we see to-day.

The first alternative is by no means impossible, since the polygon walls are due to ice-wedges and Taber (1943, p. 1512) records examples of these extending at least 30 feet from the surface, with presumptive evidence that they go much deeper. It must not be forgotten, however,



TEXT-FIG. 1 A.—Geological map of the area around Abbot's Salford showing the position of alluvium and terraces 1, 2, and 4. After Dr. M. E. Tomlinson. Scale : 1 inch to 1 mile. The extent of the photograph, Plate XI, fig. 1, is shown by the quadrilateral S.W. of Abbot's Salford.

TEXT-FIG. 1 B.—Enlargement of part of A, at scale of 4 inches to the mile. The dark arrow shows the direction of view of the air photograph. The area over which polygonal structures can be recognized is indicated.

that these ice-wedges narrow downwards and presumably extend to unequal depths from the surface, so that the pattern made by them about 30 feet below ground could be expected to have many incomplete polygons with much narrower walls. As far as can be seen from Pl. XI, fig. 1, neither of these effects shows in the crop markings as the ground moves across the terrace edge on to Keuper Marl. Moreover, although frost wedges of gravel are visible not uncommonly in Pleistocene deposits of various ages in the south Midlands, they usually end only a few feet below the surface. Ten feet is an unusual depth and the deepest I have seen, in Paxford Gravels and Stretton Sands at Stretton on Fosse in south Warwickshire, was not bottomed at 17 feet though it was here rapidly narrowing. I am, therefore, inclined to reject the first possible explanation (*a*) and to accept the second, that the pattern was formed after the terrace had been cut through. It is then reasonable to equate these features of " permafrost " with a later period of

maximum cold, the acme of the Würm glaciation. This is most likely to be the period of low sea-level ((vi) of p. 406) which preceded the aggradation of the cold climate gravels of No. 2 Terrace, correlated with the first retreat stages of the Irish Sea Glacier (Wills, 1938).

REFERENCES

ARKELL, W. J., 1947. *The Geology of Oxford.* Clarendon Press.

FROST, R. E., 1952. Interpretation of permafrost features from airphotos. In *Highway Research Board Special Report No.* 2, Frost Action in Soils, pp. 223–246. Washington.

LEFFINGWELL, E. DE K., 1919. The Canning River Region, Northern Alaska. *U.S. Geol. Surv.*, Professional Paper 109.

RILEY, D. N., 1945. Archaeology from the air in the Upper Thames Valley. *Oxoniensia*, viii–ix, 83.

SHOTTON, F. W., 1953. The Pleistocene deposits of the area between Coventry, Rugby and Leamington. *Phil. Trans. Roy. Soc.* B, ccxxxvii, 209.

TABER, S., 1943. Perennially frozen ground in Alaska ; Its origin and history. *Bull. Geol. Soc. Amer.*, liv, 1433–1548.

TOMLINSON, M. E., 1925. River terraces of the lower valley of the Warwickshire Avon. *Quart. Journ. Geol. Soc.*, lxxxi, 137.

—— 1935. The superficial deposits of the country north of Stratford on Avon. *ibid.*, xci, 423.

WILLS, L. J., 1938. The Pleistocene development of the Severn from Bridgnorth to the sea. *ibid.*, xciv, 161.

GEOLOGY DEPARTMENT,
UNIVERSITY OF BIRMINGHAM.

EXPLANATION OF PLATE XI

FIG. 1.—Oblique air photograph of fields on Abbot's Salford Hill in July, 1958, with differential ripening of crops revealing a polygonal pattern. (Photo : W. A. Baker).

FIG. 2.—Vertical air photograph showing patterned ground in Northern Alaska. (Photo : Dr. R. F. Black.)

Fig. 1.

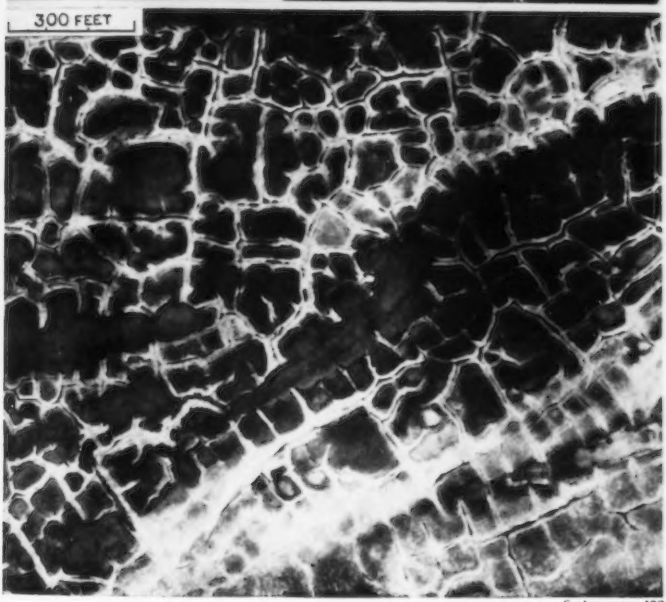


Fig. 2.

facing page 408

LARGE-SCALE PATTERNED GROUND.

Origin of Convoluted Laminae

By John E. Sanders

Abstract

Comparison of streaked-out " ripples " formed by the drag effects of a current passing over a watery, yet cohesive sediment bottom with convoluted laminae formed within beds of fine-grained sandstone suggests a common origin. Application of Bagnold's recent discoveries on the behaviour of cohesionless sediment in flowing fluids to the problem results in a modification of Kuenen's hypothesis of origin of the convolutions. According to the new interpretation, convolutions arise when formerly cohesionless sand grains become cohesive after deposition and respond to increased shearing due to higher current velocity by a décollement-type of adjustment with the plane or planes of adjustment located within, or in some cases at or below the base of the growing sandstone bed. Convolute " anticlines " in cohesive sand are thought to serve the same function as that played by current ripple-marks in cohesionless sand, i.e., they create additional bottom relief in order to increase the drag and restore equilibrium to the added shearing stress imposed by the current that cannot be counterbalanced by grain-to-grain encounters.

I. Introduction

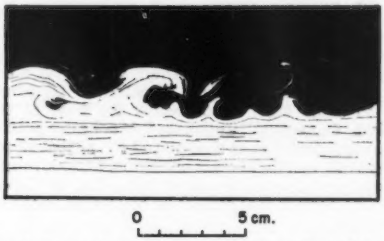
Attenuated ripple-like structures formed of lutite and overlain by arenite (Text-fig. 1) have been reported from many localities and given several different names and interpretations by various authors (Sorby, 1908; Henderson, 1935; Lamont, 1936; 1938; 1939a; 1939b; 1941; 1957; Kuenen, 1953b; Kuenen and Menard, 1952; Kuenen and Prentice, 1957; Prentice, 1956; Shrock, 1948; Sullwold, 1959; Walton, 1956). Only those which have been formed simultaneously with transportation and deposition of the covering sand bed are considered here. Interested readers are referred to the References for further discussion of the other modes of origin and nomenclature of these features. These streaked-out ripples are considered to be the fine-grained cohesive sediment analogues of the current ripple-marks which occur only in coarser, cohesionless sediment. If correct, then these ripple-like features in mud offer a possible explanation for the convoluted laminae that occur in very fine-grained sandstones, whose grains were at times cohesionless, at other times cohesive.

The writer expresses his thanks to Prof. Ph. H. Kuenen, Groningen, The Netherlands, for helpful comments and criticisms on a draft of this paper.

II. Review of Relevant Sediment Transport Mechanics

G. K. Gilbert (1914) first clearly differentiated between sediment transportation in water streams by suspension, on the one hand, and by

traction, on the other. Gilbert's experiments were particularly concerned with traction transport of sand by clear water. From them he recognized three phases of traction: (1) smooth phase; (2) dune phase; and (3) antidune phase. In all phases water moved the sand grains as individuals, or in other words, the grains were cohesionless. In the dune phase the surface of the sand assumed regular, rhythmic asymmetric forms; these migrated slowly downstream as erosion took place on their gentler upstream faces and deposition occurred on their



TEXT-FIG. 1.—Sorby's specimen of green slate from Langdale. Volcanic sand (black) overlies laminated volcanic mud. Along the contact the mud has been skimmed off and streaked out into attenuated " ripples ". Note extreme deformation of " ripple " at left, which has been bent forward onto the next " ripple " to its right and further deformed. Also note spray-like wisps on downcurrent side of some " ripples ". Current from left to right. (Traced from Sorby's (1908) photograph, Plate XIV).

steeper downstream faces. In the antidune phase the sand waves were larger, more symmetric, and rounded in profile, but moved *upstream* instead of downstream; hence their name antidune. The rapid water motion caused erosion on the downstream face and deposition on the upstream face of the next ripple downcurrent; the sand waves thus progressed upstream even though all sand grains were in rapid transit downstream. Another peculiarity of the antidune phase, seen both in nature (Cornish, 1899) and in the experiments (Gilbert, 1914), is that the water surface covering the antidunes assumes the same wave shape as the sand " waves "; the water waves also move upcurrent with the sand " waves ", a peculiarity that is not true in the case of ordinary ripple marks. This characteristic of upstream movement of the sand " wave " in the antidune phase and consideration of other meanings for *dunes* led Bucher (1919, p. 165) to apply the name " regressive sand waves " to them as an alternative for " antidune ". Lamont's application of " antidune " to features formed in mud is rejected on the grounds of the effects of cohesion.

Working independently and nearly simultaneously, Hjulström (1935, 1939) and Bagnold (1937) discovered that fine-grained sediment, once

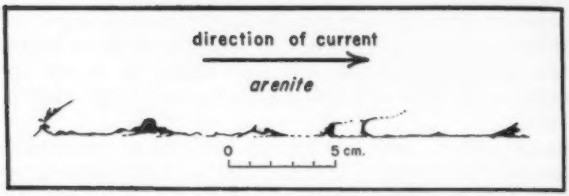
deposited, tends to behave differently toward a current than the settling velocity relationships of individual small grains would lead one to predict. Hjulström, studying natural streams, and Bagnold, studying air blowing over portland cement, found that a greater current was required to erode the fine detritus from the bottom than to keep such detritus in suspension once it had been lifted into the current. Hjulström expressed this by the now-familiar erosion-transportation-deposition curve; this phenomenon has been named the Hjulström effect (van Straaten, 1954, p. 69).

The explanation of this behaviour of fine-grained sediment lies in the cohesion between smaller particles and in the fact that they present a hydraulically smoother surface to the current, hence tending to prevent eddies of turbulent flow from impinging on the bottom and distributing the drag over the entire surface (Inman, 1949, p. 53; 57; 61).

Bagnold (1954; 1956) has recently provided the theoretical explanation for the behaviour of cohesionless sand-size and larger grains in fluids by evaluating the effect of grain-to-grain encounters on the fluid flow. Bagnold's analysis adequately explains Gilbert's observations on the first two phases of traction transport; it does not consider the antidune phase. Bagnold has demonstrated that transverse ripples in cohesionless sand being transported by water (the case for air is different under many flow conditions) are form-drag features that arise spontaneously from the bottom in an attempt to balance a deficit of shearing resistance in the bottom *vis-à-vis* that imposed by the fluid flow. As sand transport first begins, adequate shearing resistance is provided by grain-to-grain encounters, but as the flow intensity increases, shearing is transmitted from the fluid faster than resistance to shearing is provided by the grain encounters. When this deficit increases sufficiently, ripple-marks in the sand arise to increase the frictional resistance offered by the bottom in order to restore the balance. Hence, ripple-marks in cohesionless sand (or ripples at the interface between two fluids of different density—the Helmholz boundary waves; see also experiments with immiscible fluids of different density conducted by Reynolds, 1883, and de Candolle, 1883) may be considered as surfaces of greater friction, not as surfaces of least friction, as proposed for ripple-marks by King (1916) and by Bucher (1919, p. 160; 178; 200–201; 207). In the case of cohesionless sand, the ripple-marks disappear when more violent motion of the individual grains causes increased numbers of grain-to-grain encounters which again generate adequate resistance to shearing. The controls on size of the ripples have not been definitely established; grain size and the pattern of internal turbulence (Gilbert, 1914, p. 248), however, seem to be important factors.

III. Streaked-out "Ripples" in Lutite

In light of these findings on the mechanics of sediment transport of cohesionless grains, important differences are to be expected where forces of cohesion between individual particles become large and no grain-to-grain encounters are provided by the bottom to resist shearing. As shearing stress intensity increases in the fluid flow over cohesive grains, therefore, a deficit will continue to exist on the side of the bottom, building up to the point where ordinary transverse current



Text-fig. 2.—Streaked out lutite formed in experimental ditch by passage of turbidity current from left to right. Note wisp-like points of two "ripples" just to right of centre. (After Kuenen and Menard, 1952, fig. 3, p. 90).

ripple-marks would tend to form if the material were cohesionless sand. But, if the bottom be cohesive hydroplastic mud when these stress conditions prevail, then the formation of streaked-out ripple-like forms would seem to be the only alternative reaction that could be expected as a means of increasing bottom resistance. Such ripple-like forms would be directly analogous to ordinary small-scale current ripples in cohesionless sand and would form only where the bottom material behaved as a dense fluid and individual grain-to-grain encounters were not possible.

Proof that some ripple-like forms in lutite were made during the passage of the current consists of evidence that bottom relief existed in the mud at the time sand was deposited. Small-scale foreset lamination on the lee side of the lutite "ripple" is conclusive proof, as pointed out by Lamont (1957; see Text-fig. 2). Multiple deformation of a single ripple-like form also seems to be indicative of origin by current shearing. Sorby's specimen (Text-fig. 1) is instructive in this connection, for it shows repeated nappe-like folds that involve not only lutite, but a thin layer of the overlying sand. The lee-side wisps of mud noted by Henderson (1935) and also found in Kuenen's experiments (Text-fig. 3) also suggest syn-depositional origin by current shearing.

The examples cited above refer to ripple-like forms whose orientation

is similar to that of transverse current ripple-marks. Features aligned parallel to current direction that are analogous to longitudinal ripple-marks may also be expected, but the writer is not personally acquainted with any examples (e.g. Sullwold, 1959).

IV. Convoluted Laminae in Sand

Convoluted laminae in fine-grained sand have been much discussed in recent years. Renewal of interest in this phenomenon is due to Rich (1950); Kuenen (1952, p. 31; 1953a, p. 1056; and 1953b, p. 16) proposed the name "convolute bedding"; and considered the problem of the origin of the convolutions in great detail (1953b,

Text-fig. 3.—Streaked-out "ripples" in lutite (black) showing cross-laminated silt on down-current side of "ripple". Current from right to left. Based on Lamont's sketch of a specimen from the Dalveen Group, Gala-Tacannon, Dalveen Pass, Dumfriesshire (Lamont, 1957, fig. 1, p. 473).

p. 14–21); Sanders (1956) and ten Haaf (1956) suggested the more appropriate designation "convolute lamination"; ten Haaf reviewed the problem of the origin of the convolutions.

It is profitable to recall Rich's (1950, p. 729) description of the convoluted laminae found in the Silurian rocks of the Aberystwyth area, Wales, even though his interpretation of the origin of these features has been shown to be in error by Kuenen who (1953b) subsequently found examples in which laminae in convolute "anticlines" had been truncated at the anticlinal crest, whereas adjacent "synclines" contained sets of inclined laminae resembling smallscale foreset beds. Kuenen also found overturned ripple lamination and overturned foreset fillings of the "synclines".

Kuenen's discoveries prove beyond all doubt that convolutions arise as a syn-depositional process and rule out all previous explanations which call upon post-depositional slumping, sliding, gliding, or slipping. Ksiazkiewicz (1951) discussed "slip bedding" in the flysch of the Polish Carpathian Mountains and cited as examples features that are

identical with convoluted laminae. He later (1958) modified the definitions as follows:

> " Convolute bedding—no horizontal slipping.
> Slip bedding—convolution distorted by slipping, but continuity of bedding (lamination) is not broken. Numerous recumbent folds, in extreme cases chunks of shales folded together with sandstones " (1958, p. 142).

The question of the role of sliding in the formation of convoluted laminae was raised again by Dzulynski, Kuenen, and Ksiazakiewicz (1958, p. 1112–1113) to explain examples of multiple independent sets of convolutions within the same bed in which the upper set deformed independently of the lower set. Further discussion of sliding as a requirement for the origin of the convolutions will be found on a subsequent page.

Sullwold (1959) suggested that convoluted laminae may be related to the wisps of mud that project upward into an overlying sandstone layer from an underlying bed of mud. He proposed that convoluted laminae may be nothing more than load folds whose upper parts have been removed by submarine scour which have been subsequently covered by sediment. Sullwold's interpretation of the origin of convoluted laminae must be rejected in light of Kuenen's evidence on syn-depositional origin of the convolutions, but the writer shares the idea that a relationship may exist between the streaked-out lutite ripples and convoluted laminae, as is indicated beyond.

Holland (1959) related convoluted laminae to turbidity-current action, but rejected Kuenen's (1953b) suggestion of a relationship with the current-ripple mechanism because the ground plan of the convoluted " folds " in his specimens was so irregular. Holland attributed convolutions to " rapid deposition, together with the possibility of hydroplastic flow in response to suction . . . " (1959, p. 233). As did Ksiazkiewicz (1951), Holland noted that the convolutions occur in calcareous siltstones.

Before continuing the discussion of the origin of convolutions, some further facts and inferences that are independent of the mode of origin will be discussed.

All observers of convoluted laminae have remarked on the fact that these disturbances are limited to very fine-grained sand and coarse silt. ten Haaf (1956) reported that the largest grains he was able to measure in convoluted laminae range from 0·06 to 0·1 mm.; the writer's own observations agree. Sediments of this grain size lie in the boundary range between smaller grains which show the Hjulström effect and larger grains which do not show this effect. Furthermore, study of the convolutions reveals that during part of the process of deposition of the bed in which these occur the grains behaved in a cohesionless state, whereas during other parts of the process they evinced cohesion. The

detailed explanation for this contrasting cohesive behavour of the grains is not known to the writer, but its existence is clearly demonstrated by the following sequence of events that can be inferred to have occurred in the origin of the convolutions, no matter what explanation is adopted to account for them.

1. Deposition of sand with parallel- and/or current-ripple lamination. In this phase the sand grains behave as individuals (are cohesionless). The laminated sand may or may not comprise the upper part of a graded bed.
2. Deformation of the laminated sand, without loss of internal structure. In this phase the sediment being deformed shows cohesion, but at the same time, however, grains may be eroded and deposited as individuals, without cohesion. Sediment that is eroded from the rising " anticlines " and deposited in adjacent " synclines " (either coming from the " anticlines " or from the current above), though cohesionless during transfer of position, may become cohesive again when deposited, for many examples are known of over-steepened or overturned foreset laminae in the " synclines " on the down-current side of " anticlines ". Not all convoluted laminae show this effect of anticlinal truncation and synclinal filling, however.
3. Repetition of Stage 1, with deposition of laminated- and/or cross-laminated sand; grains cohesionless.

The foregoing sequence represents a simple case in which only one set of convolutions is present. Stage 2, however, may be repeated one or more times in alternation with Stage 3 before deposition of the bed ceases. This repetition is indicated by the occurrence of several independent sets of convolutions within a single sandstone bed with non-convoluted layers intervening.

Alternatively, convoluted " anticlines " may not be truncated and the " synclines " may not be filled with cross-laminated sediment. Perhaps the convolutions are merely an expression of the possibility that grains intermediate in size between lutite, which always shows cohesion (pellets excepted), and arenite, which is generally cohesionless, may be either cohesionless or cohesive, depending upon conditions.

Consideration of the streaked-out " ripples " of lutite discussed previously, the proof that convolution takes place as a syn-depositional process, and the alternatively cohesionless and cohesive behavour of sand grains in the range of grain sizes in the convolutions provides important clues to the understanding of the origin of the convoluted laminae. On the basis of these, the writer offers the following new interpretation:

(1) Fine-grained sand or coarse silt is deposited and re-worked by the current, forming parallel laminae and/or current-ripple marks, with current-ripple lamination. The latter indicates downcurrent tractional shifting of the ripples by the current without further significant sedimentation from above. Deposition from above during rippling is shown by superposition of ripple forms without internal truncation of the laminae (Sorby, 1908, p. 181–182; Pls. 15, 16). Pulsations of current velocity are implied, because the sand must first be deposited

and afterward drifted forward by a current whose velocity was not great enough to put the sand into suspension and carry it away, but which was large enough to shift it along the bottom by traction. The origin of these pulsations in current velocity is not revealed from study of convoluted laminae; but pulsations clearly occurred, as evidence presented beyond also substantiates.

(2) An increase in shearing stress is placed on the bottom, where slight cohesion has already resulted between the fine grains. Dzulynski, Ksiazkiewicz, and Kuenen (1959, p. 1112) remark that in experimental turbidity currents the deposit changes quickly: " In the course of a minute or less, compaction causes the bed to contract to half its thickness, and the hydroplasticity is gradually much reduced..." Such compaction may give rise to the necessary cohesion.

Once cohesion between grains becomes important, the bottom is no longer able to react by forming current ripple-marks, as it would normally do if the grains were cohesionless. Instead, the bottom responds to the increased shearing stress imparted from the fluid by developing a series of " anticlines " that are analogous to the streaked-out " ripples " of lutite discussed previously. A similar mechanism is held to operate in both, namely that cohesion prevents formation of typical current ripple-marks but the highly hydroplastic condition of the sediment permits sediment flow. The increase of shearing intensity is caused by increased current velocity, but the reason for this increase is not shown by the convoluted sediment.

The " anticlines " grow by a décollement-type of adjustment with respect to layers below. The length and thickness of the deformed layers may change, but the deformation dies out downward either abruptly or gradually. In the former case, adjustment is concentrated in a single layer; in the latter, it may be distributed through several layers. A décollement-type zone of adjustment is suggested by two lines of evidence:

(*a*) The " anticlines " tend to be narrow and sharp, whereas the " synclines " tend to be wide and flat-bottomed. Features with this geometry are diagnostic of décollement; in reality the " synclines " are but passive features that are outlined by the rising " anticlines " as adjustment takes place along a gliding or slipping surface below. The geometry of deformation requires further study; it is possible that the anticlines rise by lengthening of the deformed layer and by flow of material from both sides towards anticlined crests.

(*b*) Multiple sets of convolutions occur within a single bed in which deformation of each set has occurred independently of other sets. If no décollement-type of adjustment took place this independence could not exist.

(3) As the " anticlines " grow in response to the forces in the current

which give rise to form-drag features on the bottom, the Bernoulli effect operates over their crests, as noted by Kuenen (1953b). The more rapid velocity of the current over anticlinal crests therefore tends to cause erosion of sediment from the crests; this sediment may be deposited as foreset laminae in the lee of the " anticline ", namely, in the " syncline " next downcurrent. Current drag may cause the anticlines to " heel over " in a downcurrent direction and to become overturned.

(4) Erosion of growing " anticlines " and concomitant filling of flat-bottomed " synclines " tends to restore a smooth sediment surface. The shearing intensity of the current, however, may demand that bottom relief be maintained, or even increased. Owing to the cohesion of the sediment, this relief can be provided only by growth of " anticlines ". The cohesive-cohesionless behavour of the sand grains tends to defeat the attempts to restore stress equilibrium and promotes instability. That the " anticlines " continued to grow even after deposition of foreset laminae in the " synclines " is proved by the steepening and even overturning of the foreset laminae on the downcurrent side of the " anticline ".

(5) The current eventually slows down and equilibrium is restored. The bed is commonly smooth on its upper surface when deposition has ceased; its uppermost parts are generally composed of evenly laminated sediment. Between the evently laminated sediment and the convoluted layers below, however, ordinary current ripple-marks or ripple-drift laminae may be found. The progression: convolutions, current-ripple marks or ripple-drift laminae, evenly laminated sediment suggests that the current velocity is diminishing and lends further support to the concept that high current velocities are required for the convolution process.

After an interval of decrease the current velocity may increase again and repeat the whole process of convolution and its sequential aftermath. Such repetitions also imply pulsations in current velocity, but yield no clue as to why such velocity increases occur.

The author's explanation differs from previous explanations in two respects: (1) It insists on syn-depositional deformational adjustment of cohesive sand layers along a basal plane or planes of décollement-type of adjustment located either within the sandstone bed or at its base as an integral part of the origin of convoluted laminae; and (2) it contains a new interpretation of the forces that cause the growth of the " anticlines ".

Failure to distinguish between the different effects of gravity sliding after deposition and lateral adjustment caused by frictional drag of the current during sedimentation may be the explanation of the confusion over the question of sliding in the origin of convoluted

laminae. Dzulynski, Ksiazkiewicz, and Kuenen (1959, p. 1112–1113) re-admitted sliding as a process involved in fashioning convolutions and allow that any and all forms of gliding were considered admissable.

The present writer infers that the deformation originated as a result of frictional drag caused by the current, and that adjustment to this deformation took place within or at the base of the sandstone bed during deposition of the bed. Adjustment seems to have occurred at the base of the sandstone bed in the example found by Kopstein (1954, p. 22–23; fig. 16) and Sullwold (1959, Pl. 1, fig. 3); such cases merge into wholesale sliding of the bed suggested by Ksiazkiewicz (1958) for the origin of " slip bedding ". It may be imagined that adjustment could occur simultaneously at the base of the bed and at a slightly higher zone within the sand itself. Adjustment along the contact between beds of sand and mud might be expected to cause disturbance of the mud; where the base of the bed is perfectly plane, however, adjustment probably occurred within the sand. This question requires further investigation.

A complete distinction is intended between the syn-depositional deformation within the sand connected with convoluted laminae and the post-stratification distortions caused by slumping. The first alternative to the earlier ideas of gravity sliding as a force in the development of convolute " anticlines " was provided by Kuenen (1953b) from the similarity in ground plan view of eroded beds containing convolutions and beds containing only current-ripple lamination. The only points of difference arise from the new interpretation of ripple-marks provided by Bagnold (1956), which was not available to Kuenen in 1953, and considerations of cohesion.

Kuenen suggested that an upward suction over the " anticlines " would be caused by the Bernoulli effect on normal current ripple-marks and that to this pressure would be added the stresses caused by sedimentary loading in the " synclines ". Local slippage or adjustment with respect to layers below must have been involved in this process, but no mention of it was made. Kuenen implied that the lateral shortening effect was caused by squeezing out of sediment from the " synclines " into the " anticlines ". Flow of sediment out of the synclines in both directions is demanded by this mechanism; the laminae in the synclines should be thinner than those in the anticlines.

The Bernoulli effect suggested by Kuenen certainly operates during the formation of convoluted laminae, but in the opinion of the present writer, Bagnold's (1956) explanation of the origin of ripple-marks combined with considerations of cohesion provide a more satisfying answer than that contained in the second mechanism invoked by Kuenen. Bagnold has shown that at certain flow intensities shearing stresses in the current require form-drag features and bottom roughness

in order to restore equilibrium. In cohesionless sand, ripple-marks form; but, in cohesive sediment the writer alleges that surface roughness can be provided only by growth of " anticlines " with décollement-type of adjustment below. If sand can be alternately cohesive and cohesionless the conditions for the origin of convolutions may be met.

The growth of the " anticlines ", therefore, is held to be due to the same factors that cause ordinary current ripple-marks, but the process is modified by the cohesive-cohesionless behavour of fine-grained sand. Cohesive sand can form " anticlines " only where form-drag features are dictated, whereas once " anticlines " begin to grow, cohesionless sand may fill in the " synclines " or be eroded from the rising " anticlines ", thus tending to smooth the bottom. When this happens and bottom roughness is still required by the shearing intensity of the current, the " anticlines " will continue to grow, deforming the synclinal fillings in the process. Only when the current velocity has diminished to the point where lower shearing intensities are applied to the bottom from the current and a smooth bottom is the stable form will the process of forming convolutions cease.

The foregoing remarks apply to transverse convolutions that are analogous to transverse current ripple-marks. A comparable mechanism may relate longitudinal convolutions (ten Haaf, 1956) to longitudinal current ripple-marks. This question needs further study; important insights into it have been noted by Dzulynski and Slaczka (1959, p. 224–225) and Dzulynski, Ksiazkiewicz, and Kuenen (1959, p. 1113).

The writer suggests that experiments to substantiate the proposed explanation of convoluted laminae might be valuable. It is predicted that relatively large current velocity requirements for convoluted laminae may be found; if so, then convoluted laminae might indicate quantitative paleogeographic data of the greatest significance concerning the flow conditions that prevailed during deposition.

As far as the writer is aware, no modern examples of convoluted laminae have been found. The phenomenon is known only from alleged turbidite sequences in the geologic record; as yet no examples of it have been reported from sediment cores taken on the modern deep-sea floor where other deposits that are inferred to have been made by turbidity currents have been reported. If turbidity currents are responsible for convolutions, then further inquiry is required into the causes of the velocity fluctuations invoked here as part of the process of origin of convolutions. According to the theory of turbidity currents, the sediment load itself governs current velocity. Convolutions are anomalous in this respect according to the theory offered here, for velocity fluctuations that are independent of the uniformly fine-grained sediment are required.

REFERENCES

BAGNOLD, R. A., 1937. The transport of sand by wind. *Geogr. Journ.*, lxxxix, 409–438.

—— 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proc. Roy. Soc.*, A, ccxxv, 49–63.

—— 1956. The flow of cohesionless grains in fluids. *Phil. Trans. Roy. Soc.*, A, ccxlix, 235–297.

BUCHER, W. H., 1919. On ripples and related sedimentary forms and their paleogeographic interpretation. *Am. Journ. Sci.*, N.S., xlvii, 149–210; 241–269.

CANDOLLE, C. DE, 1883. Rides formées à la surface du sable dépose au fond de l'eau. *Arch. Sci. Phys. Nat.*, Genève, ser. 3, ix, 241–287.

CORNISH, V., 1899. On kumatology. *Geogr. Journ.*, xiii, 624–626.

DZULYNSKI, S., and SLACZKA, A., 1959. Directional structures and sedimentation of the Krosno beds (Carpathian flysch). *Soc. geol. Pologne, Ann.*, xxviii (1958), 205–260.

DZULYNSKI, S., KSIAZKIEWICZ, M., and KUENEN, Ph. H., 1959. Turbidites in flysch of the Polish Carpathian Mountains. *Bull. Geol. Soc. Amer.*, lxx, 1089–1118.

GILBERT, G. K., 1914. The transportation of debris by running water. *U.S. Geol. Survey Prof. Paper* 86, 263 p.

HENDERSON, S. M. K., 1935. Ordovician submarine disturbances in the Girvan district, Scotland. *Trans. Roy. Soc. Edin.*, lviii, 487–509.

HJULSTRÖM, F., 1935. Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bull. Geol. Inst. Univ. Upsala*, xxv, 221–528.

—— 1939. Transportation of detritus by moving water, *in* Trask, P. D. ed. *Recent Marine Sediments*, 5–31.

HOLLAND, C. H., 1959. On convolute bedding in the Lower Ludlovian rocks of north-east Radnorshire. *Geol. Mag.*, xcvi, 230–236.

INMAN, D. L., 1949. Sorting of sediments in the light of fluid mechanics. *Journ. Sed. Pet.*, xix, 51–70.

KING, W. S. H., 1916. The nature and formation of sand ripples and dunes. *Geogr. Journ.*, xlvi, 189–209.

KOPSTEIN, F. P. H. W., 1954. Graded bedding of the Harlech Dome. *Rijksuniv. Groningen, Inaug. Diss.*, 97 p.

KSIAZKIEWICZ, M., 1951. Slip bedding in the Carpathian Flysch. *Ann. Soc. Geol. Pologne*, xix (1949), 493–501 (In Polish ; English summary, 502–504).

—— 1958. Submarine slumping in the Carpathian Flysch. *Ann. Soc. Geol. Pologne*, xxviii (1958), 123–150.

KUENEN, PH. H., 1952. Paleogeographic significance of graded bedding and associated features. *Proc. Kon-Ned. Akad. Wetensch. Amsterdam*, B, lv, 28–36.

—— 1953a. Significant features of graded bedding. *Am. Assoc. Pet. Geol. Bull.*, xxvii, 1044–1066.

—— 1953b. Graded bedding, with observations on Lower Paleozoic rocks of Britain. *Verhandl. Kon. Ned. Akad. Wetensh. Amsterdam, Afd. Nat.*, xx, 1–47.

—— 1957. Sole markings of graded graywacke beds. *Journ. Geol.*, lxv, 231–258.

KUENEN, PH. H., and MENARD, H. W., 1952. Turbidity currents, graded and non-graded deposits. *Jour. Sed. Pet.*, xxii, 83–96.

KUENEN, PH. H., and PRENTICE, J. E., 1957. Flow markings and load-casts. *Geol. Mag.*, xciv, 173–174.

LAMONT, A., 1936. Palaeozoic seismicity. *Nature*, cxxxviii, 243–245.

—— 1938. Contemporaneous slumping and other problems at Bray Series, Ordovician and Lower Carboniferous horizons, County Dublin. *Proc. Roy. Irish Acad.*, xlv, 1–32.

LAMONT, A., 1939a. Landslips in the geological record. *Quarry Managers' Journ.*, xxi, 348–353; 391–394; xxii, 13–16; 89–91; 94; 170–174.

—— 1939b. Antidunes in geology: *Brit. Assoc.*, Dundee Programme, Sept. 1 (Abs.), p. 253.

—— 1941. Irish submarine disturbances. *Quarry Managers' Journ.*, xxvi, 123–127; 150–151.

—— 1957. Slow antidunes and flow marks. *Geol. Mag.*, xciv, 472–480.

PRENTICE, J. E., 1956. The interpretation of flow-markings and load-casts. *Geol. Mag.*, xciii, 393–400.

REYNOLDS, O., 1883. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and the law of resistance in parallel channels: *Phil. Trans. Roy. Soc.*, clxxiv, 935–982.

RICH, J. L., 1950. Flow markings, groovings, and intrastratal crumplings as criteria for the recognition of slope deposits, with illustrations from Silurian rocks of Wales. *Am. Assoc. Petr. Geol. Bull.*, xxxiv, 717–741.

SANDERS, J. E., 1956. Oriented phenomena produced by sedimentation from turbidity currents and in subaqueous slope deposits (Abs.). *Jour. Sed. Pet.*, xxvi, 178.

SHROCK, R. R., 1948. *Sequence in layered rocks.* New York, McGraw-Hill, 507 p.

SORBY, H. C., 1908. On the application of quantitative methods to the study of the structure and history of rocks. *Quart. Journ. Geol. Soc.*, lxiv, 171–232.

STRAATEN, L. M. J. U. VAN, 1954. Composition and structure of Recent marine sediments in The Netherlands. *Leidse Geol. Meded.*, xix, 1–110.

SULLWOLD, Jr., H. H., 1959. Nomenclature of load deformation in turbidites. *Bull. Geol. Soc. Amer.*, lxx, 1247–1248.

TEN HAAF, ERNST, 1956. Significance of convolute lamination. *Geol. en Mijnbouw*, xviii, 188–194.

WALTON, E. K., 1956. Limitations of graded bedding and alternative criteria of upward sequence in the rocks of the Southern Uplands. *Trans. Geol. Soc. Edin.*, xvi, 262–271.

DEPARTMENT OF GEOLOGY,
YALE UNIVERSITY,
NEW HAVEN,
CONNECTICUT.

The Strength and Stress-Strain Characteristics of Oakdale Coal under Triaxial Compression

By D. W. Hobbs

(PLATE XII)

Abstract

Laboratory measurements of the effect of a confining pressure on the strength and stress-strain characteristics of a metallurgical coking coal are described. Several-fold increases in the strength, the Young's modulus and the elastic strain at failure were found as the confining pressure was increased to 5,000 lb./in.^{2}. The results are discussed in relation to various criteria of failure. It was found that failure was represented by Coulomb's equation relating shear stress and normal stress, provided the observed angles of fracture were not influenced by local edge stress concentrations.

I. Introduction

A complete knowledge of the way in which coal breaks under various stress systems is essential in studying the best methods of winning coal. Further, measurement of the elastic properties of coal enables predictions to be made of the behaviour of coal under strata pressures and also provides some insight into the physical structure of coal.

Although uniaxial compressive strength measurements on coal have been made for many years, few measurements have been reported of the strength of coal under triaxial compression. In 1930 Muller investigated the dependance of compressive strength on confining pressure of a bituminous coal and more recently Voblikov and Protod'yakonov (1955) carried out triaxial experiments on a Russian Anthracite. The value of the results obtained by these authors is difficult to assess since the coal specimens were compressed in arbitrary directions and no mention was made of the speciman size. Both of these factors have been shown to influence coal strength (Pomeroy 1957, Evans and Pomeroy 1958) and Muller's results suffer from the further disadvantage that no indication was given of the number of specimens tested. Murrell (1958) has investigated the strength of two coals, Cwmtillery from the Garw seam and Hards from the Barnsley seam under triaxial compression.

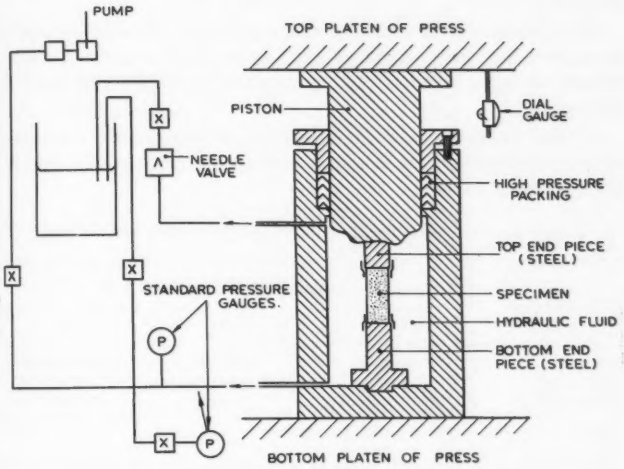
In this paper are recorded the results of triaxial compression tests on cylindrical specimens of a single coal, Oakdale from the Meadow seam, at room temperature, at various confining pressures up 5,000 lb./in.^{2}.

II. Description of Apparatus and Method of Measurement

The apparatus used in these experiments has already been described by Murrell (1958) and only a brief description will be given here.

A cylindrical specimen of Oakdale coal was contained in an oil-filled pressure vessel (Text-fig. 1). The specimen was mounted between

two steel end pieces and was protected from the oil by an impermeable membrane. The hydraulic pressure was built up in the oil in the pressure chamber by the advance of a steel piston, which was initially clear of the top end piece, and the confining pressure was maintained constant at the required value by means of a needle valve. The piston was then allowed to come into contact with the top end piece and an additional axial load was applied to the coal specimen to fracture it. A spherical seating unit was employed to ensure that the coal specimen



TEXT-FIG. 1.—Triaxial Apparatus.

was loaded axially. The onset of fracture of a specimen was normally marked by the load remaining constant whilst the strain increased although occasionally a sudden drop in load occurred.

The measured movement of the piston into the pressure vessel included both the strain along the axis of the coal specimen and the strain in the apparatus. Separate experiments were made, without coal specimens, to calculate and so eliminate the strain in the apparatus. The load was applied to the piston, at a rate of approximately 100 lb./sec., by either a 10-ton or a 100-ton Avery Universal Testing Machine.

The frictional forces between the piston and the cylinder were measured immediately before the piston engaged with the top end piece and it was assumed that this force remained constant throughout the experiment. This may introduce some small but incalculable error.

III. Preparation of Specimens

The coal used in these experiments was from the Meadow seam at Oakdale Colliery with N.C.B. coal rank No. 301 and percentage volatiles approximately 22·3 (dry, ash-free).

Oakdale coal is extremely friable and has two well defined systems of cleat planes, which are indistinguishable on cut specimens, finely spaced and approximately at right angles to each other. In addition to these macroscopic cleat cracks the coal specimens contained random cracks and flaws.

The specimens used were of a single size, 2 in. in length by 1 in. in diameter ; they were cut using a water-flushed hollow diamond coring-bit and cut to the required length using a thin high-speed carborundum slitting-wheel.

In order to investigate the influence of the three planes of weakness on the measurements the cylinders were cut in three different orientations shown in Table 1.

Table 1.—Orientations in which the Specimens were Cored

Plane of weakness	Orientation to Specimen Axis		
	(1)	(2)	(3)
Bedding . .	parallel	parallel	perpendicular
Main cleat . .	parallel	perpendicular	parallel
Cross cleat . .	perpendicular	parallel	parallel

The specimens were cut wet and were dried under reduced pressure at a temperature of 28°C. for eight days before testing ; during this period a reduction in weight of 1 to 2 per cent. occurred. Higher temperature and high vacua were not used for fear of altering the properties of the coal.

The coal specimens were protected from the hydraulic fluid by Araldite D sleeves which were approximately 0·015 in. thick. To protect the specimen end faces from the oil, rubber sleeves were allowed to overlap the specimen by about 0·25 in. at either end. The rubber sleeves also assisted the insertion and removal of the specimen and steel end pieces from the pressure vessel.

Araldite D has a Young's modulus of $4{\cdot}5 \times 10^5$ lb./in.^{2} and a Poisson's ratio of 0·36, values in close agreement with the properties of coal. This suggests that the principal effect of an Araldite D sleeve will be to strengthen the coal specimen by slightly increasing its effective size and also by reducing the influence of surface irregularities.

IV. Experimental Results

The specimens were cut from a number of blocks collected at the same time from run-of-mine supplies. Since it is probable that appreciable differences occur between one block and another, specimens were, in general, selected at random. Some additional tests that were considered desirable, marked with an asterisk in Table 2, were carried

Table 2.—Triaxial Strengths

Orientation to Specimen Axis	Confining Pressure, lb./in.²	Axial Fracture Stress, lb./in.²	Axial Yield Stress, lb/.in.²
Bedding planes parallel .	0	320 ± 50	280 ± 40
	500	3,680 ± 170	3,170 ± 110
Main cleat planes parallel	1,000	4,480 ± 490	3,770 ± 400
	2,000	6,940 ± 860	6,110 ± 650
	3,000	9,980 ± 970	8,940 ± 740
	4,000	13,780 ± 940	11,940 ± 740
	5,000	15,330 ± 370	13,210 ± 650
Bedding planes parallel .	0	825 ± 160	760 ± 150
	500	4,070 ± 220	3,440 ± 190
Main cleat planes	1,000	6,480 ± 770	5,730 ± 820
perpendicular.	2,000	6,740 ± 900	6,240 ± 780
	3,000	10,420 ± 1,030	9,230 ± 930
	4,000	12,330 ± 1,050	11,360 ± 770
	5,000	16,810 ± 220	14,310 ± 220
Bedding planes	0	770 ± 140	720 ± 140
perpendicular.	100*	2,890 ± 190	2,530 ± 200
Main cleat planes	250*	3,510 ± 340	3,040 ± 290
parallel.	500*	5,990 ± 400	5,380 ± 440
	1,000	6,160 ± 560	5,440 ± 400
	2,000	8,160 ± 770	6,940 ± 630
	3,000	11,110 ± 1,170	9,950 ± 1,090
	4,000	12,670 ± 1,260	10,970 ± 1,060
	5,000	17,000 ± 190	15,070 ± 360

* Specimens cut from single block of coal.

out on specimens cut from a single block of coal. Eight specimens were tested at each confining pressure.

(a) *Fracture Stresses and Yield Stresses*

In this paper it is assumed that the elastic limit and the limit of proportionality of the stress-strain curve coincide. The yield stress is defined as the stress at the limit of proportionality. The determination of the yield stress depends on the sensitivity of the strain measuring device to detect a departure from linearity of the stress-strain curve.

The axial fracture stress and the axial yield stress at various confining pressures up to 5,000 lb./in.² are given in Table 2. The figures quoted

are the mean and the standard error of the mean. The variations of the fracture stress and the yield stress with confining pressure, for confining pressures greater than 500 lb./in.^{2}, were to a first approximation linear.

The specimens with bedding and main cleat planes parallel to their axes were weaker than those with the other two orientations for confining pressures less than 2,000 lb./in.^{2}.

(b) *Mode of fracture and fracture angles*

Photographs of typical fractured specimens are shown in Plate XII ; as can be seen the specimens failed along planes inclined to the specimen axes.

For a homogeneous material an irregular type of conical fracture would be expected. In the case of Oakdale coal this mode of fracture was only observed in a few of the specimens, all of which had been crushed at a confining pressure of 5,000 lb./in.^{2}. In general the specimens fractured along one or more planes inclined to the specimen axis and frequently the specimens failed along a series of parallel planes. Sometimes when more than one fracture plane occurred the planes intersected to form wedges, which then split the coal by transverse tension resulting in tensile separation across planes parallel to the axis of the specimen.

The fracture planes tended to be influenced by the planes of weakness (bedding planes, main and cross cleat planes) the normal to the fracture plane and the normal to the weakness plane lying in the same plane. At low confining pressures the mode of fracture was influenced by all three planes of weakness but at high confining pressures the cross cleat planes had no influence on failure.

The angle of fracture is the angle between the normal to the fracture plane and the major principal stress (i.e. the confining pressure since compressive stresses are negative according to convention).

The use of Araldite D sleeves enabled the angle of fracture to be measured directly to about $\pm$ 1° without removing the sleeve (Plate XII). The angles of fracture are given in Table 3.

The angles of fracture for the specimens with bedding and main cleat planes parallel to their axes were in general smaller than those observed for the two other orientations.

(c) *Strain measurements*

Only the differential axial strain could be measured since the specimens were subjected initially to a hydrostatic pressure which was maintained constant through-out the test. Typical curves of the variation of the differential axial strain with the axial stress, for specimens of Oakdale coal subjected to triaxial compression, are shown in Text-fig. 2.

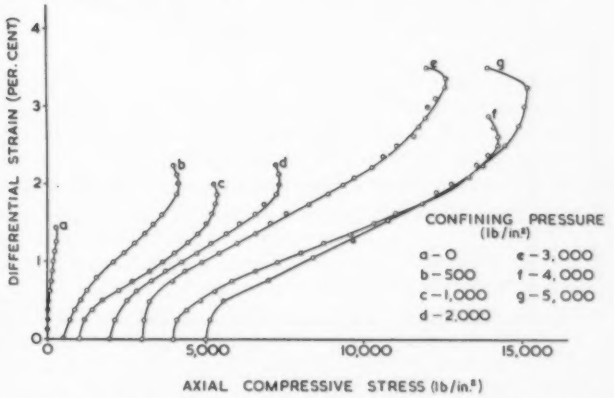
TABLE 3.—ANGLES OF FRACTURE

Confining Pressure, lb./in.²	Angle of Fracture (degrees)		
	Bedding planes parallel, main cleat planes parallel to specimen axis	Bedding planes parallel, main cleat planes perpendicular to specimen axis	Bedding planes perpendicular, main cleat planes parallel to specimen axis
0	11·9 ± 2·7	14·4 ± 2·4	12·9 ± 1·8
250	—	—	12·0 ± 1·9
500	18·9 ± 1·7	15·1 ± 2·5	15·7 ± 1·5
1,000	13·9 ± 2·2	20·1 ± 1·7	20·6 ± 2·1
2,000	16·1 ± 3·2	22·5 ± 4·9	21·0 ± 2·1
3,000	17·9 ± 2·2	20·4 ± 2·3	20·5 ± 2·4
4,000	19·8 ± 1·4	23·4 ± 1·3	24·3 ± 2·2
5,000	24·3 ± 1·6	22·4 ± 1·4	24·6 ± 1·0

Three features are evident on the stress-strain curve, these are :—

(i) The initial non-linear portion of the stress-strain curve which is attributed mainly to the closing of the cracks in the coal. To estimate the strain due to bedding down between the coal specimens and end pieces, and end pieces and piston, experiments were carried out on a steel specimen. Since the strain in the steel for a given stress increment does not change with stress, any decrease in strain rate with applied stress would be caused by bedding down but this was found to be negligible.

(ii) All specimens, except those tested at atmospheric pressure



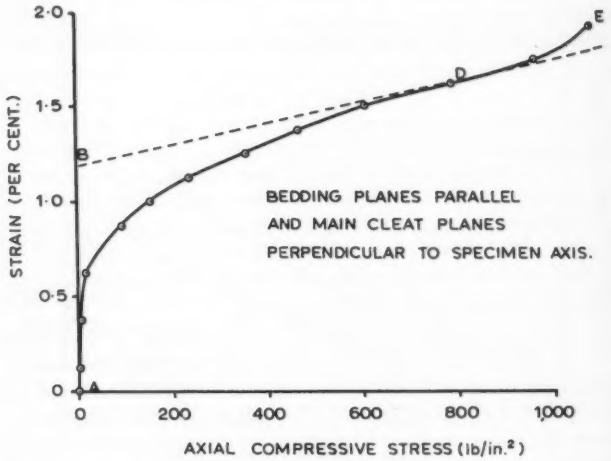
TEXT-FIG. 2.—Typical Stress-Strain Curves for Specimens with Bedding and Main Cleat Planes Parallel to the Specimen Axis.

(Text-fig. 3), exhibited a range of elastic linearity of stress with strain. The Young's modulus in compression was determined from the linear portion of the curve. The Young's modulus for the specimens tested at atmospheric pressure was determined at the point of inflection of the stress-strain curve. Since it is probable that at the point of inflection the cracks are only partially closed low values will be observed for the Young's modulus of the bulk coal.

(iii) The final non-linear portion of the stress-strain curve which is thought to be due to pre-rupture cracking. If Oakdale coal is imagined to be a granular material then it is possible that the pre-rupture cracking can be attributed to the failure of the bonding between individual granular components.

The results of strain measurements are given in Table IV. The strain intercept AB (Text-fig. 3) is the strain attributed mainly to the closing of the cracks. The strain BD is an estimate of the elastic strain of the framework of the coal up to the yield point. The strain DE is the strain due to yielding or pre-rupture cracking.

The strain AB, attributed to the closure of cracks, was approximately constant at all confining pressures. Only one exception exists, this relates to specimens tested at zero confining pressure, and hence to conditions under which the macroscopic main cleat cracks were not fully closed.



TEXT-FIG. 3.—Typical Stress-Strain Curve for Specimen Crushed at Atmospheric Pressure.

V. Discussion of Results

Increasing the confining pressure up to 500 lb./in.^{2} produced large increases in the axial fracture stress, axial yield stress and the Young's modulus. These large increases can probably be attributed to the closing of the macroscopic cleat and random cracks by the confining pressure, apparent closure of these cracks occurring at a confining pressure of the order of 500 lb./in.^{2}.

Terry (1959) found that the elastic wave velocity continues to increase slightly over the range of stresses corresponding to the linear portion

Table 4.—Strain Measurements

Orientation to Specimen Axis	Confining Pressure, lb./in.^{2}	Young's Modulus, $\times 10^6$ lb./in.^{2}	AB Strain, per cent	BD Strain, per cent	DE Strain, per cent
Bedding planes parallel.	0	0·58 ± 0·15	0·42 ± 0·08	0·65 ± 0·13	0·12 ± 0·04
	500	3·21 ± 0·43	0·27 ± 0·07	0·95 ± 0·11	0·43 ± 0·08
Main cleat planes parallel.	1,000	3·24 ± 0·65	0·45 ± 0·09	0·98 ± 0·17	0·53 ± 0·11
	2,000	4·02 ± 0·39	0·24 ± 0·05	1·02 ± 0·09	0·44 ± 0·14
	3,000	4·33 ± 0·43	0·31 ± 0·07	1·37 ± 0·10	0·98 ± 0·17
	4,000	6·08 ± 0·74	0·34 ± 0·03	1·35 ± 0·16	0·80 ± 0·12
	5,000	5·42 ± 0·27	0·22 ± 0·04	1·49 ± 0·09	1·35 ± 0·31
Bedding planes parallel.	0	1·19 ± 0·21	0·84 ± 0·05	0·67 ± 0·05	0·16 ± 0·05
	500	2·56 ± 0·38	0·39 ± 0·07	1·23 ± 0·18	0·63 ± 0·11
Main cleat planes perpendicular.	1,000	3·79 ± 0·54	0·42 ± 0·07	1·34 ± 0·11	0·50 ± 0·08
	2,000	4·03 ± 0·62	0·31 ± 0·05	1·10 ± 0·09	0·42 ± 0·08
	3,000	3·75 ± 0·68	0·29 ± 0·06	1·72 ± 0·13	0·95 ± 0·26
	4,000	5·21 ± 0·42	0·38 ± 0·09	1·37 ± 0·07	0·75 ± 0·19
	5,000	5·68 ± 0·18	0·34 ± 0·06	1·65 ± 0·09	1·16 ± 0·13
Bedding planes perpendicular.	0	1·72 ± 0·26	0·51 ± 0·11	0·49 ± 0·07	0·11 ± 0·04
	100	2·87 ± 0·25	0·46 ± 0·05	0·86 ± 0·04	0·32 ± 0·03
Main cleat planes parallel.	250	3·55 ± 0·37	0·21 ± 0·03	0·97 ± 0·09	0·30 ± 0·07
	500	5·31 ± 0·48	0·47 ± 0·08	0·93 ± 0·09	0·26 ± 0·08
	1,000	4·21 ± 0·45	0·54 ± 0·12	1·11 ± 0·09	0·39 ± 0·07
	2,000	4·58 ± 0·38	0·45 ± 0·08	1·11 ± 0·10	0·54 ± 0·15
	3,000	5·04 ± 0·60	0·40 ± 0·05	1·14 ± 0·14	0·43 ± 0·14
	4,000	5·02 ± 0·49	0·50 ± 0·06	1·30 ± 0·09	0·72 ± 0·16
	5,000	6·46 ± 0·22	0·37 ± 0·07	1·57 ± 0·04	0·71 ± 0·09

of the stress-strain graph and to explain this he assumed that some of the cracks were not completely closed but continue to close elastically under increasing stress. If this hypothesis is correct then the increases in the Young's modulus of the coal observed in these experiments, may be caused by the increased resistance to deformation of the unclosed cracks as the confining pressure increases the cracks closing elastically at all confining pressures.

The differential strain due to the closing or partial closing of the cracks was greatest for specimens with bedding planes perpendicular to the axis in accordance with Terry's (1959) suggestion of a system of flat disc like cracks orientated parallel to the bedding planes.

The angles of fracture and the mode of fracture may be dependant, to a large extent, on the end (Coker and Filon, 1957) and the edge (Mylonas, 1955) effects. The Young's modulus of the steel end pieces is about 50 times as high as that of coal and when the end pieces are

loaded shearing stresses are up because of friction, which are directed towards the centre of the end faces ; barrelling in the middle part of the specimen will therefore occur, setting up tensile stresses.

However, in the present work fracture generally occurred along a series of parallel planes so that local edge stress concentrations do not appear to affect rupture.

A number of theories have been proposed to predict and explain the failure of materials under various stress systems. The theories are strictly applicable only to materials which are homogeneous, isotropic and elastic. Between certain stress limits Morgans and Terry (1958) have shown that coal behaves as an elastic material but coal exhibits anisotropy in strength (Pomeroy, 1957) and elasticity (Morgans and Terry, 1958). Despite this it is of interest to consider the present results in terms of the predictions of the various criteria of failure which have been proposed. These criteria discussed by Nadai (1950), and will only be mentioned briefly here.

As can be seen from Tables 2, 3, and 4 the maximum principal stress, the maximum strain, the maximum shear stress and the strain energy criteria of failure are not applicable to coal.

(a) *Griffith's Theory*

Griffith (1921) considered a material containing a random distribution of elliptic cracks each crack being so spaced as to be uninfluenced by all other cracks, and showed that even when the applied forces were compressive, tensile stresses could be set up at the ends or edges of the crack of sufficient magnitude to cause tensile failure.

Griffith's equations are for $3\sigma_1 + \sigma_3 \leq 0$ where $\sigma_1 > \sigma_3$

$$\kappa = \frac{-(\sigma_1 - \sigma_3)^2}{8(\sigma_1 + \sigma_3)} \quad . \quad . \quad . \quad . \quad (1)$$

$$\cos 2\theta = -\tfrac{1}{2}\frac{(\sigma_1 - \sigma_3)}{(\sigma_1 + \sigma_3)} \quad . \quad . \quad . \quad (2)$$

where κ is the intrinsic tensile strength, a constant for the material, and θ is the angle of fracture.

The material is assumed to be subjected to a biaxial stress system in accordance with Mohr's assumption that the intermediate principal stress has no influence on failure.

The values of the intrinsic tensile strength and the angles of fracture for one particular specimen orientation, obtained from equations 1 and 2 and the yield stresses of Table 2 are given in Table 5 ; similar results are obtained for the two other specimen orientations.

The intrinsic tensile strength predicted from Griffith's theory does not have a constant value and the theoretical angles of fracture are

TABLE 5.—INTRINSIC TENSILE STRENGTH AND ANGLE OF FRACTURE DETERMINED FROM GRIFFITH'S EQUATIONS

Orientation to Specimen Axis	Confining Pressure, lb./in.^{2}	Intrinsic Tensile Strength, lb./in.^{2}	Angle of Fracture
Bedding planes perpendicular. Main cleat planes parallel.	0	90	30
	100	281	31·2
	250	296	32·6
	500	506	32·7
	1,000	383	34·9
	2,000	341	37·0
	3,000	466	37·2
	4,000	406	38·3
	5,000	632	37·7

greater than the observed values (Table 3). The difference may be attributed to :

(i) The anisotropic nature of Oakdale coal. Oakdale coal does not contain an isotropic distribution of cracks since there is a tendancy for the cracks to be aligned parallel to the bedding and cleat planes

(ii) The change in shape of the cracks. The confining pressure closes the macroscopic cracks ; there is a change in shape and a change in volume of the microscopic cracks. Upon application of the axial load all the cracks except those parallel or nearly parallel to the direction of the axial load will close partially or completely increasing the crack anisotropy.

(iii) The propagation of inherent cracks and to the formation of new cracks. When specimens are crushed at atmospheric pressure compacting of the bulk coal occurs with the propagation of inherent cracks and probably also the formation of new cracks. Visible signs of cracking can be seen and heard before yielding of the specimen commences.

(b) *Mohr's criterion*

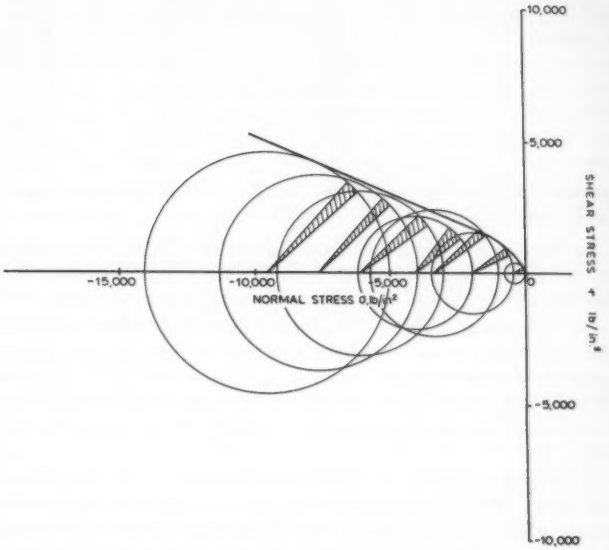
Mohr (1914) suggested that a material will fail either by flow or fracture when the shearing stress along the plane of failure has increased to a certain value determined by some function of the normal stress on the plane

$$\text{i.e. } \tau = f(\sigma)$$

where τ is the shearing stress along the plane of failure and σ is the normal stress on the plane of failure.

The Mohr circles and envelope for one particular specimen orientation are drawn in Text-fig 4. As already stated the variation of the axial yield stress with the confining pressure, for confining pressures greater than 500 lb./in.^{2}, is to a first approximation linear, this implies a linear form for Mohr's envelope.

If Mohr's envelope represents the failure surface then the angles of fracture for confining pressures greater than 500 lb./in.^{2} should be constant. On the Text-figure the radii from the centre of the Mohr circles are drawn at angles of 2θ to the σ axis where θ is the observed angle of fracture. The angles of fracture are in every case lower than



TEXT-FIG. 4.—Mohr's Envelope for Specimens with Bedding Planes Parallel and Main Cleat Planes Perpendicular to the Specimen Axis.

than those predicted by Mohr's theory but the divergence decreases as the confining pressure increases.

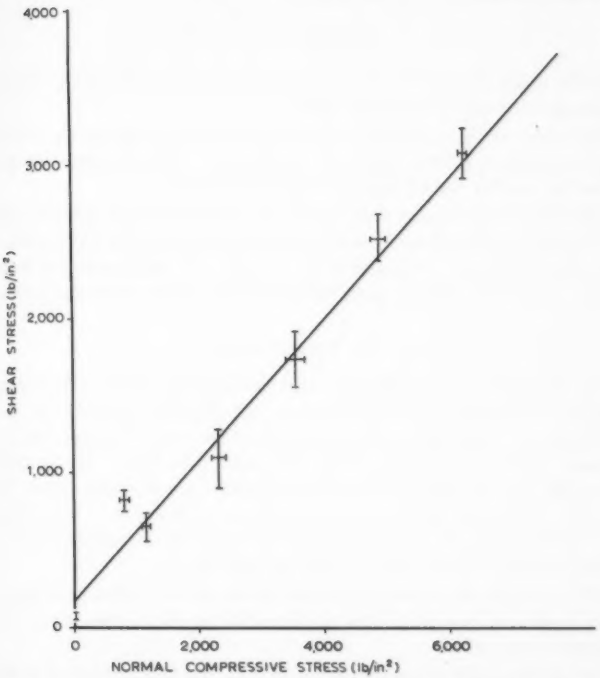
The discrepancies between the angles calculated from Mohr's theory and the observed angles may be due to the anistropic nature of Oakdale coal. Seigel (1950) has shown on the basis of a generalisation of Mohr's criterion that in a material containing a single plane of weakness :

1. The normal to the plane of probable failure and the normal to the weakness plane should lie in the same plane.
2. The fracture plane is rotated towards the weakness plane.

Similar conclusions will apply to materials containing more than one plane of weakness. The specimens of Oakdale coal tested had their weakness planes either parallel to the direction of the major principal stress (i.e. perpendicular to the greatest compressive stress), or in the

plane of the major and minor principal stresses. Both factors were obeyed, the smallest angles of fracture occurring when both the bedding and main cleat planes were parallel to the specimen axis.

Thus Seigel has provided an explanation for the discrepancies between the angles calculated from Mohr's theory and the observed angles



TEXT-FIG. 5.—Variation of Shear Stress with Normal Stress for Specimens with Bedding and Main Cleat Planes Parallel to the Specimen Axis.

and has provided further support to the suggestion already made that local edge stress concentrations do not appear to affect rupture.

The condition under which the coal fractures will not be altered by the presence of weakness planes, i.e. the coal cylinders fracture when the shearing stress along the plane of failure has increased to a certain value determined by some function of the normal stress on the plane. To determine this function the shear stresses and normal stresses were calculated from the observed angles of fracture (Table 3). The results for one particular specimen orientation are plotted in Text-fig. 5. The

variations of the shear stress with the normal stress can be represented quite adequately by linear equations of the form

$$\tau = \tau_c - \mu\sigma \quad . \quad . \quad . \quad . \quad (3)$$

i.e. Coulomb's equation, where τ is the cohesive or shear strength and μ is the coefficient of internal friction.

$$\text{Let } \mu = \tan\phi \text{ then } \phi < \frac{\pi}{2} - 2\theta$$

θ is the angle of fracture, the angle between the normal to the failure plane and the major principal stress.

The value of the coefficient of internal friction lies between 0·45 and 0·47 depending on the specimen orientation. The relationships are therefore similar for all three specimen orientations.

Thus for a material containing one or more planes of weakness the failure surface is defined by a curve which intersects the Mohr circles. The angle of failure being greater or less than the angle predicted from Mohr's envelope depending on the orientation of the weakness planes.

VI. Conclusions

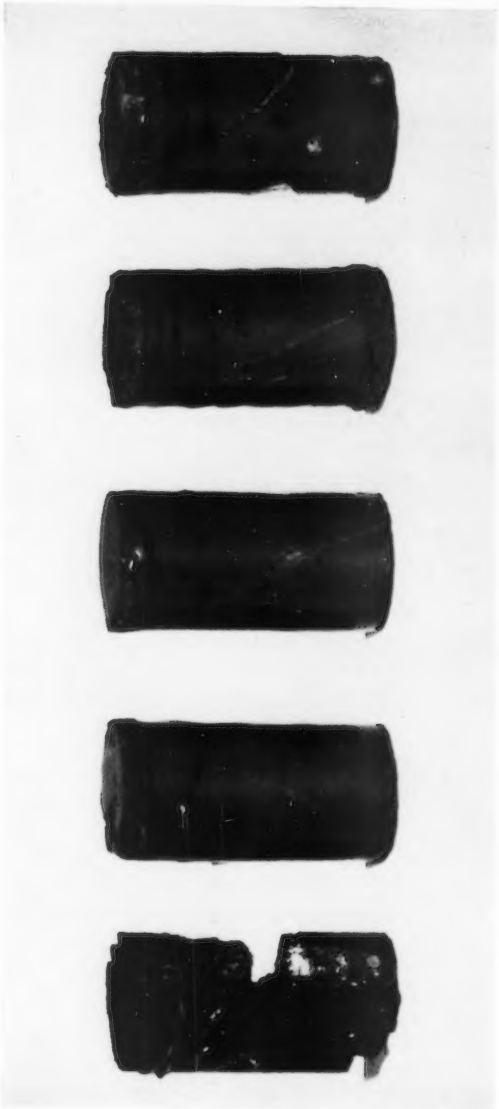
The measurements on Oakdale coal have shown that the effect of an applied confining pressure produces considerable changes in the strength and stress-strain characteristics of the coal. Several fold increases in the axial fracture stress, the axial yield stress, the Young's modulus, and the elastic strain at the yield point were observed as the confining pressure was increased from 0 to 5,000 lb./in.^{2}. Increasing the confining pressure also increased the angle of the failure surfaces relative to the direction of the axial fracture stress.

The variation of the axial fracture stress and the axial yield stress with confining pressure (greater than 500 lb./in.^{2}) was to a first approximation linear.

At low confining pressures the mode of failure was influenced by all three planes of weakness but at the higher confining pressures the cross cleat planes had no influence on failure.

All the specimens tested, with the exception of those tested at atmospheric pressure, exhibited a range of elastic linearity of stress with strain. The strength and elastic anisotropy decreased with increasing confining pressure.

None of the theories considered is wholly applicable to the results for Oakdale coal. It has been shown that provided the angles of fracture are uninfluenced by local edge stress concentrations then failure is represented by Coulomb's equation relating shear stress and normal stress with fracture occurring by shear.



FRACTURED SPECIMENS OF OAKDALE COAL.

facing p. 435

VI. Acknowledgments

The author wishes to thank Dr. I. Brodie for helpful discussion and Mr. J. L. Jarvis for his assistance with the experiments and the calculations.

This paper describes work carried out as part of the Research Programme of the Mining Research Establishment and is published by permission of Dr. W. Idris Jones, Director-General of Research in the Scientific Department of the National Coal Board. The views expressed are those of the author and not necessarily those of the Board.

REFERENCES

Coker, E. G. and L. N. G. Filon, 1957. *A Treatise on Photoelasticity*. London.

Evans, I. and C. D. Pomeroy, 1958. The Strength of Cubes of Coal in Uniaxial Compression. *Mechanical Properties of Non-Metallic Brittle Materials*, London.

Griffith, A. A. 1921. The Phenomena of Rupture and Flow in Solids, *Phil. Trans. Roy. Soc. Lond.*, ccxxi, 163.

Mohr, O., 1914. *Abhandlungen, aus den Gebiete der technischen Mechanik*, 2nd Ed. Berlin.

Morgans, W. T. A., 1958. Studies of the Rheological Behaviour of Coal. *Mechanical Properties of Non-Metallic Brittle Materials*, London.

Morgans, W. T. A. and N. B. Terry, 1958. Measurements of the Static and Dynamic Elastic Moduli of Coal. *Fuel*. xxxvii, 201.

Muller, O., 1930. Untersuchungen an Karbongesteinen zur Klarung von Gebirgsdruckfragen, *Gluckauf*, lxvi, 1601.

Murrell, S. A. F., 1958. The Strength of Coal Under Triaxial Compression. *Mechanical Properties of Non-Metallic Brittle Materials*, London.

Mylonas, C., 1955. Experiments on Composite Models with Applications to Cemented Joints. *Proc. Soc. Exp. Stress Anal.*, xii, 129.

Nadai, A., 1950. *Theory of Flow and Fracture of Solids.*, Vol. I., 2nd Ed., New York.

Pomeroy, C. D., 1957. A Simple Method for the Assessment of Coal Strength. *J. Inst. Fuel*, xxx, 50–54.

Protod'yakonov, M. M. and V. S. Voblikov, 1955. Investigation of the Breakdown of Coals and Rocks under Triaxial Compression. *Trans. Inst. Acad. Min. Sci. U.S.S.R.*, ii, 75–89. (Trans. by I.C.I. Ltd. Stevenston.)

Seigel, H. B. 1950. A Theory of Fracture of Materials and its Applications to Geology. *Trans. Am. Geophys. Un.*, xxxi, 611.

Terry, N. B., 1959. The Dependance of the Elastic Behaviour of Coal on the Microcrack Structure. *Fuel*, xxxviii, 125.

National Coal Board,
Mining Research Establishment,
Isleworth.

EXPLANATION OF PLATE XII

Typical fractured specimens of Oakdale Coal with bedding and main cleat planes parallel to the axis.

Archaean Palaeogeography of Eastern and Northern Singhbhum, Eastern India

By Kshitindramohan Naha and Subir Kumar Ghosh

Abstract

Geological studies in eastern Singhbhum and critical analysis of Dunn's published work in surrounding regions suggest that during the Archaean times a volcanic geanticlinal arc, now represented by the Dalma lavas, tuffs and agglomerates extended roughly east–west for more than 150 miles. The geosynclinal trough in the southern, concave side of the arc was filled with argillaceous sediments, thin subgraywackes and orthoquartzites derived from a land mass to the south. The trough in the northern, convex side of the arc was filled with a huge thickness of argillaceous sediments associated with graywackes, siliceous limestones, sandstones and pre-orogenic ultra-basic and basic intrusives. Both the troughs near their border with the volcanic arc were filled with pyroclastic materials.

During orogenic movements two anticlinoria were formed in the supracrustal sediments above the two troughs separated by a syncline above the geanticline, with a granulite-migmatite core in the heart of the outer geosyncline.

Studies on different aspects of the Archaean geology of eastern Singhbhum in eastern India and a critical analysis of the pioneer work of Dunn (Dunn, 1929; Dunn and Dey, 1942) in this and surrounding areas have led the present authors to suggest a palaeographic set-up in these parts of Singhbhum and adjacent regions during the Archaean times.

Significant features that shed light on the palaeogeography are:—

(*a*) An arcuate tectonic and sedimentational belt south of the Dalma lavas running from north-west of Sini (22°47′N, 85°57′E) to the west across Tatanagar to Ghatsila (22°34′N, 86°29′E) in the east, following an E to ESE course, and swerving gradually through SE to SSW in southeast Singhbhum and northeast Mayurbhanj (Dunn, 1929; Dunn and Dey, 1942). This arc is concave to the south with the fold axes in the main arc subparallel to the arcuate belt itself except along the fold-virgations and syntaxis (Naha, 1955, 1956a, 1956c, 1959).

(*b*) The presence within this belt of a vast thickness of deformed and metamorphosed dominantly argillaceous sediments with rhythmic bedding, convolute bedding and slumped sheets, together with thin arenaceous bands showing small-scale current bedding (Naha, 1956b). Metamorphosed hypabyssal basic intrusives are present in the lower part of the succession.

(*c*) A northward direction of current flow, as indicated by current bedding (Naha, unpublished work) in the Tatanagar-Ghatsila belt up to 5 miles south of the Dalma lavas, with local westward current direction near the lavas where the arc trends NS.

(*d*) A very prominent belt of lava flows, the Dalma traps, with volcanic agglomerates and tuffaceous materials (Dunn, 1929; Dunn

and Dey, 1942) of variable thickness, running parallel to the above belt along its northern edge for 150 miles from northwest of Sini to northeast of Ghatsila.* The presence of a large amount of agglomerates definitely establishes it to be a belt of ancient active volcanoes, at least partly emerging above sea.

(*e*) Persistent beds of tuffaceous phyllites and carbon-phyllites just north and south of the Dalma lava belt throughout its extension. Dunn's classic work has shown that the carbon-phyllite-pyroclastic rock association is too common to be accidental.

(*f*) The presence of a second belt of vast thickness of metasedimentary rocks north of the Dalma lavas, containing dominantly argillaceous sediments with occasional graywacke (Ghosh, unpublished work), siliceous limestones and quartzites in a highly folded and metamorphosed state. This belt passes northward into granulite facies pelitic and calc-silicate rocks which are blurred in a migmatitic milieu in Purulia and Ranchi districts.

(*g*) The presence of deformed and metamorphosed sheets of essentially concordant ultrabasic rocks (alpine type of Hess, 1955) in profusion in this belt with very common metamorphosed basic rocks.

In the light of recent ideas about island arcs and their relation to sedimentation, tectonism and volcanism in geosynclinal furrows (Vening Meinesz, 1934; Hess, 1938; Umbgrove, 1947, 1950), the above features can be co-ordinated into the following picture (Text-fig. 1-rock distribution modified from Dunn and Dey, 1942, pl. 40):—

(1) The Dalma traps represent the volcanic island arc (the geanticline where the crust has been upbuckled—not to be confused with the "geo-anticline" of Dunn and Dey (1942) which is simply an anticlinorium of the sediments) from which the lavas, agglomerates and tuffaceous materials were derived (The present distribution as shown in Text-fig. 1 is obviously somewhat modified due to folding.)

(2) In the northern (convex-outer) side of the Dalma volcanic arc was formed a trough (over a tectogene), the axis running across the Purulia and Ranchi districts near the northern border of the tract shown in the map, the region now being occupied by granulites and migmatites.

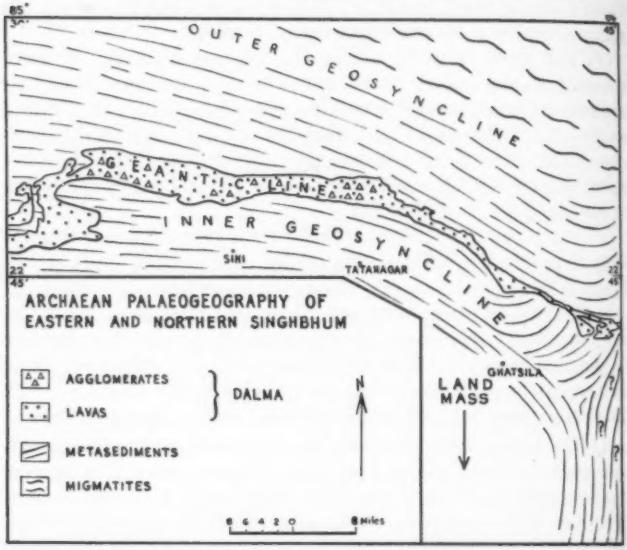
(3) In the southern (concave-inner) side of the Dalma volcanic arc was the (idiogeosyclinal) trough passing southward through continental shelf to land mass to the south, particularly in the eastern part.

In such a tectonic framework the emergent geanticlinal volcanic arc was eroded, the clastics filling rapidly the troughs just north and south forming tuffaceous and carbonaceous shales which were subsequently

* The nature of this belt further east is not known, but the attitude of folds adjacent to the belt at the eastern border (Ghosh, 1959; Naha, 1956c, 1959) suggests the presence of a northeasterly branch.

metamorphosed to phyllites. Palaeocurrent determinations from the region just bordering the Dalma volcanics in the south indicate a southward flow of material from the volcanic arc. Significant in this context is the westward palaeocurrent northeast of Ghatsila, about 4 miles west of the lavas, where the arc trends south.

The main bulk of sediments in the central part of the inner geosyncline came from the land mass to the south, forming a vast thickness



of argillaceous rocks with occasional thin subgraywackes and second-cycle orthoquartzites. The great thickness of argillaceous sediments with fine rhythmic lamination, convolute lamination and extensive slumping indicates deposition in an unstable geosynclinal trough.* Hypabyssal basic rocks were intruded in the lower part of the geosynclinal prism.

In the northern trough also a large thickness of dominantly argillaceous sediments with tuffaceous materials, graywacke, minor sandstones and siliceous limestones were laid down with intrusions of ultrabasic and basic materials, forming the outer (geotectoclinal) unit. As pointed out by Hess (1955), pre-orogenic alpine type of ultrabasic rocks are characteristically present in the axial parts of the alpine

* Consistent current direction, as shown by small-scale current bedding here, never occurs in shallow water in wide depositional troughs (Kopstein, 1954; ten Haaf, 1959).

mountains and island arcs and nowhere else.* Lavas continued to be erupted in the geanticlinal arc, while tuffaceous materials forming the youngest sediments accumulated in the bordering region of the trough.

This sedimentary-volcanic-intrusive complex forming the outer and inner geosynclines was deformed and metamorphosed during orogenic movements with the formation of two anticlinoria in the northern and southern sedimentary pile and a syncline of the Dalma volcanics above the geanticlinal infrastructure. The rocks were raised to high metamorphic grade in the cores of anticlinoria, the highest grade (granulite facies) having been reached in the centre of the outer geosyncline with the development of a migmatitic core.

Thanks are due to Professor S. Ray, of the Presidency College, Calcutta, for critically reading the manuscript.

* In the southern belt south of Ghatsila rare ultrabasic intrusions are present but they are clearly post-orogenic (Roy, 1956 ; Naha, unpublished work).

REFERENCES

Dunn, J. A., 1929. The geology of northern Singhbhum. *Geol. Surv. Ind. Mem.*, liv.

Dunn, J. A., and A. K. Dey, 1942. Geology and petrology of eastern Singhbhum and surrounding states. *ibid.*, lxix, pt. 2.

Ghosh, Subir Kumar, 1959. Migmatization in relation to regional deformation in the area around Kuilapal, West Bengal. *Quart. Jour. Geol. Min. Met. Soc. Ind.*, (in press).

Haaf, E. ten, 1959. Properties and occurrence of turbidites. *Geol. en Mijn.* (new ser.), xxi, 217–222.

Hess, H. H., 1938. Gravity anomalies and island arc structures with particular reference to the West Indies. *Proc. Amer. Phil. Soc.*, lxxix, 71–96.

—— 1955. Serpentines, orogeny and epeirogeny. *Geol. Soc. Amer., Sp. Paper* 62, 391–408.

Kopstein, F. P. H. W., 1954. Graded bedding of the Harlech dome. *Diss. Groningen*, 1–97.

Naha, K., 1955. A preliminary note on the geometry of folds around Galudih and Ghatsila, Singhbhum, Bihar. *Science and Culture*, xx, 614–15.

—— 1956a. Kyanite-chloritoid-schists from south Dhalbhum and northeastern Mayurbhanj. *Quart. Journ. Geol. Min. Met. Soc. Ind.*, xxviii, 89–100.

—— 1956b. Penecontemporaneous deformation in the pre-Cambrian metasedimentary rocks of Dhalbhum, Bihar. *ibid.*, 155–157.

—— 1956c. Structural set-up and movement plan in parts of Dhalbhum, Bihar. *Science and Culture*, xxii, 43–45.

—— 1959. Steeply plunging recumbent folds. *Geol. Mag.*, xcvi, 137–140.

Roy, S., 1956. Studies on the ultrabasic rocks of Ghatsila, Singhbhum. *Quart. Jour. Geol. Min. Met. Soc. Ind.*, xxviii, 27–32.

Umbgrove, J. H. F., 1947. *The Pulse of the Earth.* The Hague.

—— 1950. Origin of deep sea troughs in East Indies. *Rept. 18th Int. Geol. Cong.*, pt. 8, 73–80.

Vening Meinesz, F. A., 1934. Gravity expeditions at sea. *Nederl. Geod. Comm.*, ii, 1–139.

Department of Geology and Geophysics,
Indian Institute of Technology,
Kharagpur, India.

Department of Geology,
Jadavpur University,
Calcutta-32, India.

REVIEWS

BASIC GEOLOGY FOR SCIENCE AND ENGINEERING. By E. C. DAPPLES. pp. vii + 609, numerous text-figs. John Wiley and Sons, Inc., New York. Chapman and Hall, Ltd., London, 1959. Price 76*s*.

This is an introduction to physical geology and petrology intended for the use of any science student. The engineer will find the information he requires, but will himself have to deduce most of the applications to his own subject.

Clear presentation and where possible quantitative treatment illustrated by numerous well chosen maps, diagrams, and graphs has resulted in a book which will be of interest to experienced geologists as well as to the students for whom it is primarily intended. It is unfortunate that the approach is sometimes uncritical, giving little indication of the doubtful nature of some of the theories propounded or of the troubles often encountered by the geologist in reaching firm or quantitative conclusions. It would, for instance, be difficult to recognise or interpret a fossil delta in terms of the jet theory as set out for the Mississippi. In the section on glacier flow, there is considered only the extrusion flow hypothesis, even though the actual distribution of flow velocity has proved to be so different from that predicted as to discredit this proposed mechanism. Each chapter has a select bibliography, mostly American.

C. L. F.

STRATIGRAPHIC PRINCIPLES AND PRACTICE. By F. MARVIN WELLER. xvi + 725 pp., with 243 figures and 24 tables. Harper, New York, 1960. Price 80*s*.

Both the size and the scope of this book are considerable, stratigraphy being defined as the study of stratified (and some other) rocks in all their aspects. It is arranged in four parts. The first (48 pages) is introductory; the second (303 pages) concerns sedimentary rocks, including the formation of sediments, palaeoecology and tectonics; the third (249 pages) deals with stratigraphic bodies and relations; while the fourth is an appendix (80 pages) on graphic representation and on fieldwork. There are 243 figures, many of which are taken from recently published papers, mainly North American. It is essentially a text-book, written in a very readable style, in which the approach is careful, almost leisurely; no pains being spared to make even the most elementary points completely clear.

However widely one cares to define stratigraphy, correlation is the core of the subject. Dr. Weller's approach to this is highly critical and leaves one in no doubt as to the limitations of present techniques, based mainly on fossils. Such searching criticism is welcome but could, perhaps, have been balanced by a fuller treatment of the achievements made by using such techniques. These are rated by European stratigraphers as not inconsiderable.

Comprehensive treatments of this kind have the advantage of a unified approach which helps the student to integrate a number of specialized branches of geology. Dr. Weller's book does this admirably. It does not, of course, replace specialized text-books on a subject such as sedimentary rocks, although much space is given to this topic. There is, in fact, a big overlap of subject matter in this particular field and one wonders if this is really necessary and whether the book would have lost anything by being shorter. It might also be argued that a student who is sufficiently mature to profit by the third part of the book should hardly need the more elementary sections of the first two parts, some of which might have been omitted without real loss.

The practice of stratigraphy can only be learned in the field and laboratory. A good text-book, however, is an important aid in so far as it summarises the current climate of ideas and discusses the value and limitations of current techniques. Dr. Weller's book is undoubtedly a significant contribution in this field.

W. W. B.